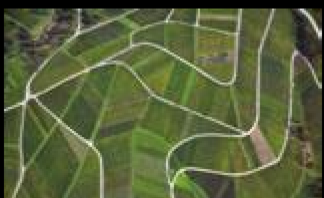



RESOURCE EFFICIENCY: POTENTIAL AND ECONOMIC IMPLICATIONS

International Resource Panel Report

UN environment
United Nations Environment Programme
International Resource Panel

Acknowledgements

Editor: International Resource Panel.

Lead authors: Paul Ekins and Nick Hughes.

Contributing authors: Stefan Bringezu, Charles Arden Clarke, Marina Fischer-Kowalski, Thomas Graedel, Maarten Hajer, Seiji Hashimoto, Steve Hatfield-Dodds, Petr Havlik, Edgar Hertwich, John Ingram, Katja Kruit, Ben Milligan, Yuichi Moriguchi, Nabil Nasr, David Newth, Michael Obersteiner, Anu Ramaswami, Heinz Schandl, Sangwon Suh, Mark Swilling, Ester van der Voet, Brian Walsh, Jim West and Henk Westhoek.

We are grateful for the valuable comments received by Hezri Adnan, Shardul Agrawala, Jacqueline Aloisi de Larderel, Chika Aoki-Suzuki, Peter Borkey, Werner Bosmans, Hans Bruyninckx, Mariano Castro Sanchez Moreno, Minpeng Chen, Patrice Christmann, Jeffrey Herrick, Tim Kasten, Lea Kauppi, Pawel Kaźmierczyk, Vijay Kumar, Yonglong Lyu, Anne Miehe, Jonathan Murphy, Kazunobu Onogawa, Antonio M. A. Pedro, Tlou Ramaru, Astrid Schomaker, Birgit Schwenk, Yoshinori Suga, Ernst von Weizsaecker, Anders Wijkman and Erinç Yeldan.

Special thanks go to Janez Potočnik and Alicia Bárcena, Co-Chairs of the International Resource Panel, and Ashok Khosla, former Co-Chair, for their contributions, dedication and commitment.

The UN Environment Secretariat team provided essential coordination and support, especially Shaoyi Li, Christina Bodouroglou, Vera Gunther and Abraham Pedroza.

Disclaimer

ISBN: 978-92-807-3645-8
Job No: DTI/2098/PA

The full report should be referenced as follows: *UNEP (2017) Resource Efficiency: Potential and Economic Implications. A report of the International Resource Panel*. Ekins, P., Hughes, N., et al.

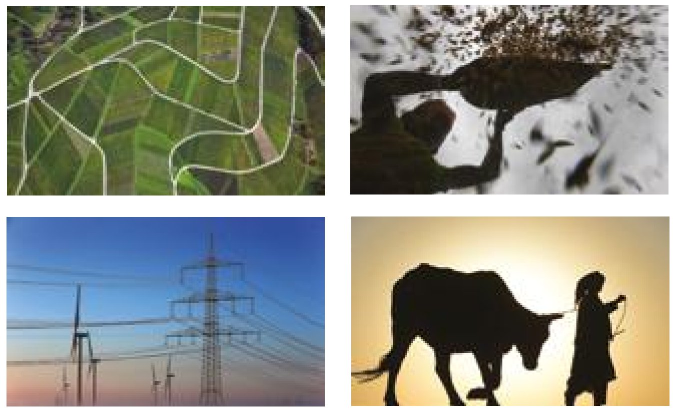
Design/layout: UN Environment Communication Division

Printed by: UNESCO

UN environment
United Nations Environment Programme

International Resource Panel

International Resource Panel Report



RESOURCE EFFICIENCY: POTENTIAL AND ECONOMIC IMPLICATIONS

A Report by the International Resource Panel

March 2017

Contents

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

List of figures

List of tables

List of boxes

Preface

Since its inception in 2007, the International Resource Panel hosted by UN Environment has been committed to providing independent, authoritative and policy relevant scientific assessments on the future state, management and use of natural resources. With the publication of 15 assessment reports and continuous dialogues with policy-makers, industry leaders and civil society, the Panel has stood out as a credible voice in the international community that underlines imperatives and the urgency for the sustainable management of natural resources and that articulates the technological and economic potential of resource efficiency and ways forward for the related public policies.

Two historic events in 2015 figure prominently on resources issues: the 2030 Agenda on Sustainable Development highlights that sustainable resource management is critical to poverty eradication and to the sustainable future we want; and the Paris Agreement on Climate Change confirms that decarbonisation must go hand in hand with decoupling economic growth from the escalating use of natural resources and environmental degradation as one of the key components for achieving the transformation towards a better tomorrow for current and future generations.

It is exactly for these reasons that the G7 at their Summit in Germany in June 2015, as Part of their increased commitment to improving their efforts in resource efficiency, asked the International Resource Panel to produce a report on the most promising potentials and solutions for resource efficiency for all countries - developed, newly industrialized and developing.

This rapid assessment report is the result of a truly collective effort by scientists and experts of the International Resource Panel who thoroughly reviewed the best science available. The findings of the report point out the importance of joining forces for acting now as well as the huge potential that resource efficiency can have, if it is implemented carefully and supported across different sectors and at multiple levels. The pressing need to invest in resource efficiency could actually lead to a positive economic outcome. The report shows how resource efficiency can lead to higher economic growth and employment, if supported by well-designed policies.

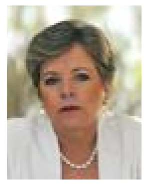
The assessment demonstrates that because many areas of resource use are relatively inefficient, the potential for resource efficiency is tremendous. This is supported by the results of the modelling undertaken for this study, which shows that resource efficiency combined with climate policy could at the same time stabilise global resource use by 2050 and boost incomes and economic growth.

Looking forward, the report demonstrates numerous examples from different countries around the world of increasing resource efficiency in different sectors. It thereby puts the different challenges ahead into perspective and illustrates how to learn from each other and how to scale up what is working.

We are very grateful to Paul Ekins and Nicholas Hughes for their tremendous effort in presenting a comprehensive up-to-date perspective for understanding the potentials and economic implications of resource efficiency. Their remarkable work gives us hope that with engaged actors, it will be possible for us to improve wellbeing for everyone and protect the planet today and tomorrow.

Co-Chairs,
International Resource Panel

Dr. Janez Potočnik,
Ljubljana, Republic of Slovenia



Dr. Alicia Bárcena,
Santiago, Chile

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

Foreword

As our population continues to grow, so does the pressure on our finite and fragile resources. Yet that threat can be turned into an opportunity to deliver the 2030 Agenda for Sustainable Development. This report highlights the massive potential of using increased efficiency as a cost-effective way to protect resources, tackle climate change and reduce our environmental footprint, while boosting economic growth, employment and development.

In 2015, the Group of Seven acknowledged this potential and asked the International Resource Panel to gather scientific evidence. In response, this report demonstrates how the right policies could cut the use of natural resources by up to 28 per cent and greenhouse gas emissions by around 74 per cent, while increasing economic activity by 1 per cent in 2050.

The scientific data is complemented by best-practice and promising solutions, with policy guidance from the Organisation for Economic Co-operation and Development. It explores how cutting taxes on appliance repairs can encourage consumers to re-use goods instead of just replacing them. It reveals that nurturing industrial co-operation can reduce waste and emissions, and stimulate new activities. And it highlights how developing compensation and transfer policies can ease the transition to more efficient practices for those dependent on the current system.

However, when it comes to improving resource efficiency, every country and region has different opportunities and challenges. So, there must be more science-policy discussion at all levels and they must be tailored to the specific priorities of each area.

For example, in the Northern Italian town of Capannori, local teacher, Rossano Ercolini, was concerned by the health risks of plans to build a waste incinerator nearby. He mobilized the community to adopt doorstep collections and a ‘pay as you throw’ system. They reduced the waste being generated by nearly 40 per cent and increased the amount being recycled to over 90 per cent. Determined to eliminate waste completely, the community is replacing disposable nappies with a washable service, adopting composting schemes and working with companies like Nespresso to make coffee capsules easier to recycle. With just 50,000 residents, Capannori has already cut waste disposal costs by over €2 million in a single year.

I hope this report will inform and inspire both public and private sector decision makers to launch many more such endeavours and would like to thank everyone who has made it possible. This includes Germany, for taking the first step in this direction as part of their Presidency of the Group of 20, and the International Resource Panel, for coordinating this work, under the leadership of the Co-chairs Janez Potočnik and Alicia Bárcena.

Erik Solheim
Under-Secretary General of the United Nations and Executive Director, UN Environment

Photo: ©AFP

Executive summary

The benefits of increased resource efficiency

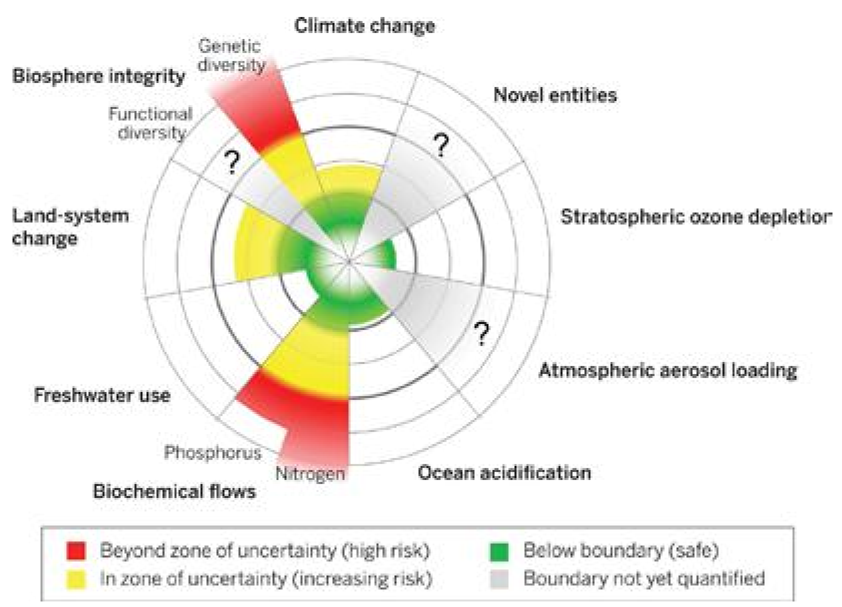
The continued growth of human populations and their economies is resulting in the emergence of billions of new middle-class consumers worldwide, and rapidly expanding urban settlements in many countries. Current patterns and processes of production and consumption raise serious questions about the ability of the planetary resource base to meet the material and energy needs of the global economy and human societies. Such provision should be timely and predictable, while avoiding excessive disruption of both global and local environmental systems.

Natural resources can be categorised as biotic and abiotic, renewable and nonrenewable, and terrestrial and marine resources. Some, like freshwater and wild fish resources are already so overexploited in many parts of the world that their use is unlikely to be sustainable in the long term. Others, like arable land, are effectively fixed in supply and are suffering from widespread erosion and degradation. Others still, such as many metals and minerals, may not be geologically scarce, but may be geographically concentrated and thus require substantial investment and long lead times to get them to market. This makes them subject to boom and bust cycles and the associated price volatility. The extraction and use of resources also creates environmental impacts, such as land degradation, biodiversity loss, and water and air pollution. Scientists have warned that "planetary boundaries", which mark the "safe operating space" for resource use and pollution, are close to being crossed, or have already been crossed, for several environmental impact categories (Figure 1) (Rockström et al., 2009b, Steffen et al., 2015).

There is great potential to address these concerns through increased resource efficiency and productivity. This involves adding greater value to resources, maintaining that value by keeping resources in use for longer, and reducing the environmental impacts associated with the whole life cycle of resources, from their extraction to their disposal. Achieving this can: reduce pressures on resource supplies, increase resource security and the resilience of societies to supply disruptions and associated price increases and volatilities, improve both local and global environmental quality, and stimulate innovation, the creation of new industries and economic competitiveness. Moreover, greatly increased resource efficiency will be necessary to meet the aspirations expressed in the Sustainable Development Goals (SDGs), agreed by the United Nations in September 2015, and the Paris Agreement on climate change adopted at the COP21 Climate Conference in December 2015.

Improving human well-being (the measurement of which is both challenging and contentious) or increasing economic output (which is more straightforward to measure), while

Figure 1: Current status of the control variables for seven planetary boundaries



Source: Steffen et al. (2015).

Note on Figure: As described by Steffen et al. (2015), "The green zone is the safe operating space, the yellow represents the zone of uncertainty (increasing risk), and the red is a high-risk zone. The planetary boundary itself lies at the intersection of the green and yellow zones. The control variables have been normalized for the zone of uncertainty; the center of the figure therefore does not represent values of 0 for the control variables. The control variable shown for climate change is atmospheric CO_2 concentration. Processes for which global-level boundaries cannot yet be quantified are represented by gray wedges; these are atmospheric aerosol loading, novel entities, and the functional role of biosphere integrity."

proportionately reducing both resource use (resource decoupling) and negative environmental impacts (impact decoupling) is a process known as double decoupling. Such decoupling is "relative" when resource use and environmental impacts increase more slowly than economic output (as shown for resources in Figure 2), or "absolute" when resource use and environmental impacts fall while the economy continues to grow (as shown for environmental impacts in Figure 2).

Trends in resource use and resource productivity

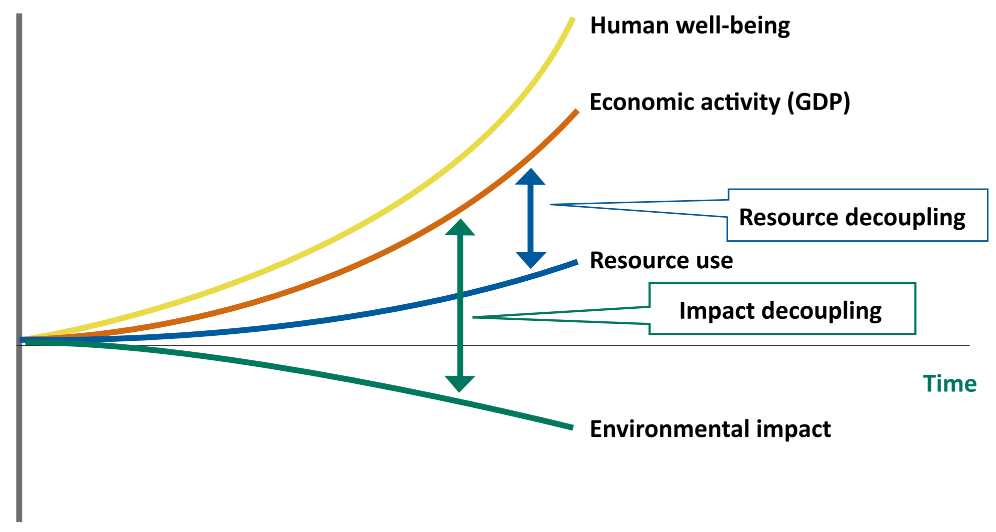
As shown in Figure 3, the G7 industrialized economies (the United States, Japan, Germany, the United Kingdom, France, Italy and Canada) tend to have much higher resource use per capita than their BRICS counterparts (Brazil, Russia, India, China, South Africa), although the gap has narrowed significantly in recent years. Figure 4 shows that material productivity in the G7 countries remains considerably above that of the BRICS economies, and continues to increase, while that of the BRICS economies has remained somewhat static. This indicates significant potential for resource decoupling in the BRICS economies as they grow. However, this divergence can also be partly attributed to the effects of international trade flows, which allow G7 countries to shift resource-intensive production to BRICS (or developing) countries.

Securing the benefits of increased resource efficiency

For priced resources, and notwithstanding price volatility, market forces tend to bring about relative decoupling over time. Nonetheless, public policy measures are required to achieve the absolute decoupling of resource use, or any kind of decoupling of environmental impacts, which are often unpriced and external to market activities.

Such measures are implemented through resource and environmental governance processes. This governance operates through mechanisms with multiple actors (governmental, commercial, civil society) and normative

Figure 2: Decoupling of resource use and environmental impacts from GDP growth



Source: UNEP (2011b), Figure 1, p.xiii.

Figure 3: Per capita domestic material consumption (DMC) in the G7, the BRICS and the global economy, 1970–2010, in tonnes

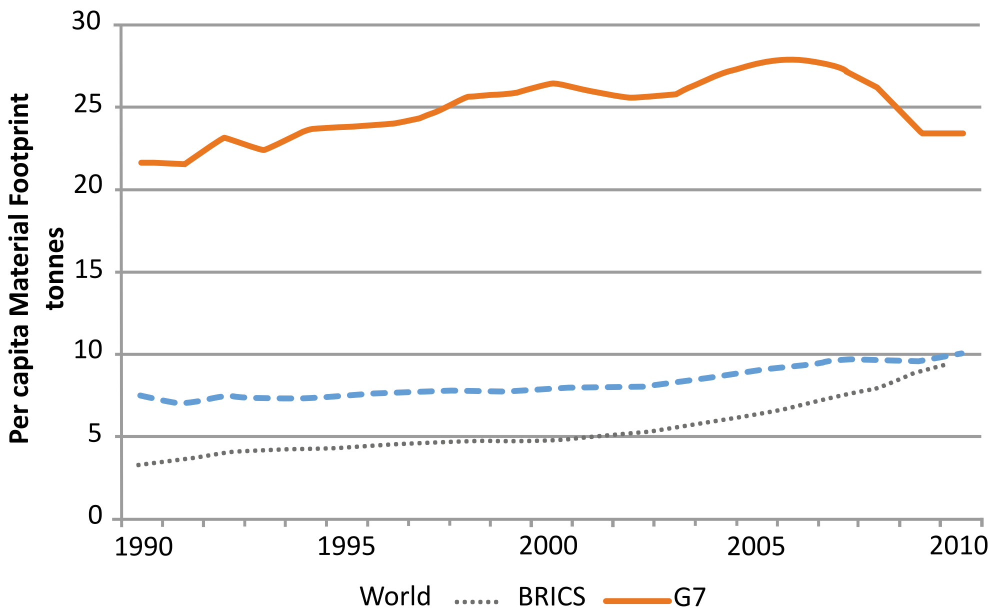
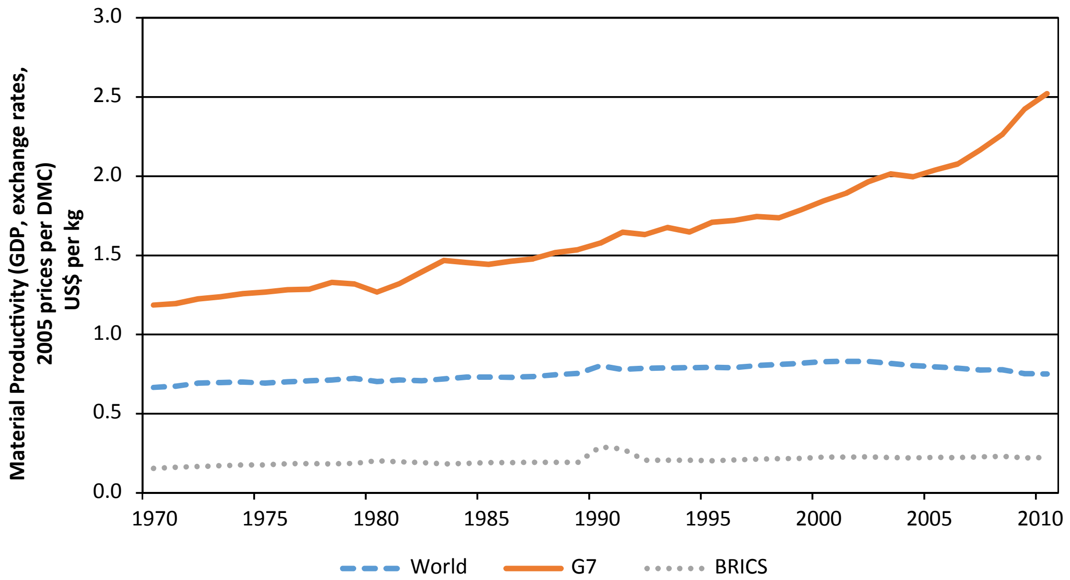


Figure 4: Material productivity (MP) in the G7, the BRICS and the global economy, 1970–2010 in US$ per kg



frameworks (enacted through treaties or legislation) at different levels (international, national and local) and on different spatial scales. The mechanisms, characterized by complex interactions, have developed substantially over recent decades. Nevertheless, they still need considerable further development if they are to achieve the systematic and absolute decoupling of resource use and environmental impacts from economic activity. This is required to secure the material and environmental foundations of economic life, and the quality of life for future generations.

Many measures that increase resource efficiency also result in improved corporate performance and competitiveness that can save consumers money and/or increase consumer satisfaction. At the macroeconomic level, increased resource efficiency and productivity can bring about higher rates of economic growth and employment. However, for reasons that are now well understood and include both market and organizational failures, these win-win economic and environmental benefits are often difficult to realize in practice. Even if barriers to resource efficiency (discussed in more detail below) are overcome, this will not necessarily lead to reductions in resource consumption. Such failure to achieve win-win benefits from resource efficiency can be due to a “rebound effect”, the phenomenon whereby financial savings arising from increased resource efficiency are then spent in ways that increase resource consumption, negating – either partially or wholly – the reduction in resource use achieved by the efficiency measure. Thus, public policy is crucial to securing all of the beneficial outcomes from increased resource efficiency.

Securing the benefits of increased resource efficiency

For priced resources, and notwithstanding price volatility, market forces tend to bring about relative decoupling over time. Nonetheless, public policy measures are required to achieve the absolute decoupling of resource use, or any kind of decoupling of environmental impacts, which are often unpriced and external to market activities.

Such measures are implemented through resource and environmental governance processes. This governance operates through mechanisms with multiple actors (governmental, commercial, civil society) and normative

frameworks (enacted through treaties or legislation) at different levels (international, national and local) and on different spatial scales. The mechanisms, characterized by complex interactions, have developed substantially over recent decades. Nevertheless, they still need considerable further development if they are to achieve the systematic and absolute decoupling of resource use and environmental impacts from economic activity. This is required to secure the material and environmental foundations of economic life, and the quality of life for future generations.

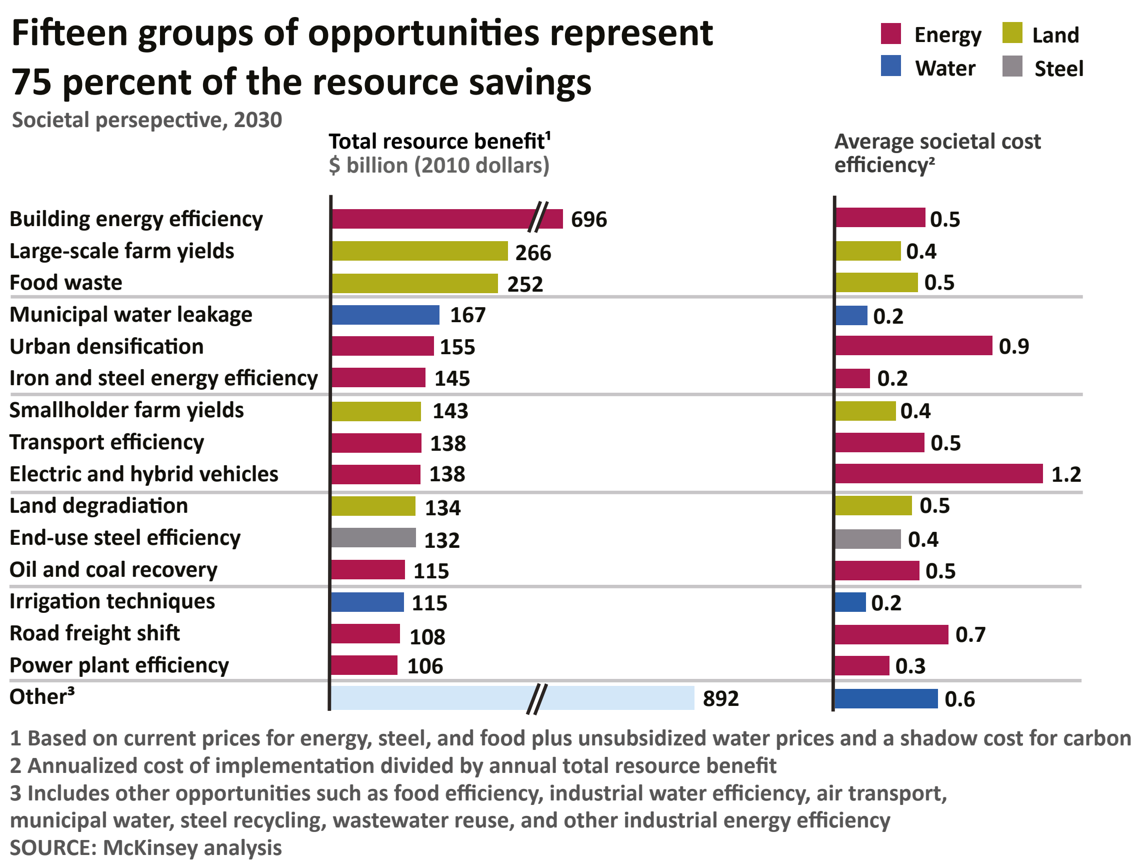
Many measures that increase resource efficiency also result in improved corporate performance and competitiveness that can save consumers money and/or increase consumer satisfaction. At the macroeconomic level, increased resource efficiency and productivity can bring about higher rates of economic growth and employment. However, for reasons that are now well understood and include both market and organizational failures, these win-win economic and environmental benefits are often difficult to realize in practice. Even if barriers to resource efficiency (discussed in more detail below) are overcome, this will not necessarily lead to reductions in resource consumption. Such failure to achieve win-win benefits from resource efficiency can be due to a “rebound effect”, the phenomenon whereby financial savings arising from increased resource efficiency are then spent in ways that increase resource consumption, negating – either partially or wholly – the reduction in resource use achieved by the efficiency measure. Thus, public policy is crucial to securing all of the beneficial outcomes from increased resource efficiency.

Sectoral breakdown of resource efficiency opportunities

There have been a number of estimates of the costs of increasing resource efficiency, with Dobbs et al. (2011, p. 10) being among the most cited. This estimate states that in 2030, implementing all the technologies considered would save private investors US$2.9 trillion per year. This Figure increases to US$3.7 trillion from a social perspective if financial subsidies to the energy, agriculture and water sectors, as well as energy taxes are removed, and carbon is priced at US$30 per tonne. Seventy percent of these savings would offer a rate of return greater than 10 percent per year. The US$900 billion investment required "could potentially create 9 million to 25 million jobs. Over the longer term, this investment could result in reduced resource price volatility that would reduce uncertainty, encourage investment, and also potentially spur a new wave of long-term innovation" (Dobbs et al., 2011, p. 12). Figure 5 shows the 15 economic sectors identified by the McKinsey Global Institute as offering the biggest potential for increased cost-effective resource efficiency.

These opportunities are examined in considerable detail in this scientific assessment report by the International Resource Panel, which is hosted by UN Environment. Part III - Chapter 1 considers a range of initiatives being pursued in the areas of public procurement, tourism, construction, food, consumer information, and lifestyles and education under the United Nations-sanctioned process of Sustainable Consumption and Production (SCP). This is followed by more detailed sectoral chapters that cover respectively: the 3Rs (reduce, re-use, recycle), resource efficiency in urbanization, food systems, mobility, power generation, and land, water and energy use in different sectors.

Figure 5: The top 15 categories of resource efficiency potential

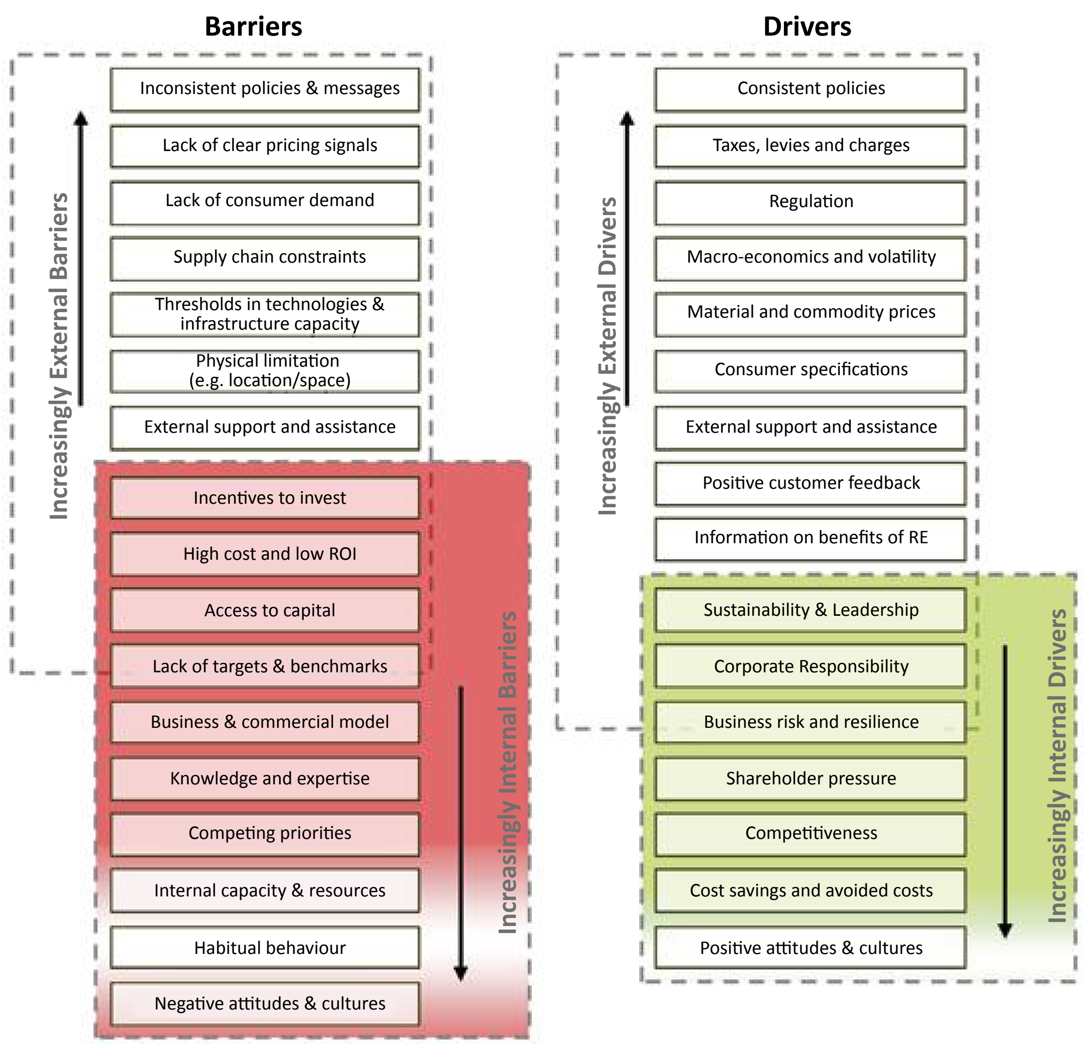


Source: Dobbs et al. (2011), Exhibit 4, p. 14.

Overcoming barriers to resource efficiency

Despite the obvious cost savings, there are many reasons why both businesses and consumers do not use resources efficiently. Figure 6 shows some of these barriers, and the drivers that may be used to overcome them. The external drivers shown to be policy-related will be essential to stimulating and strengthening the internal drivers. Unless appropriate policies are put in place,

Figure 6: Barriers to resource efficiency and drivers to address them



Source: AMEC and BIoIS (2013), Figure 1, p.vii.

resource efficiency will not increase sufficiently to address the challenges outlined above.

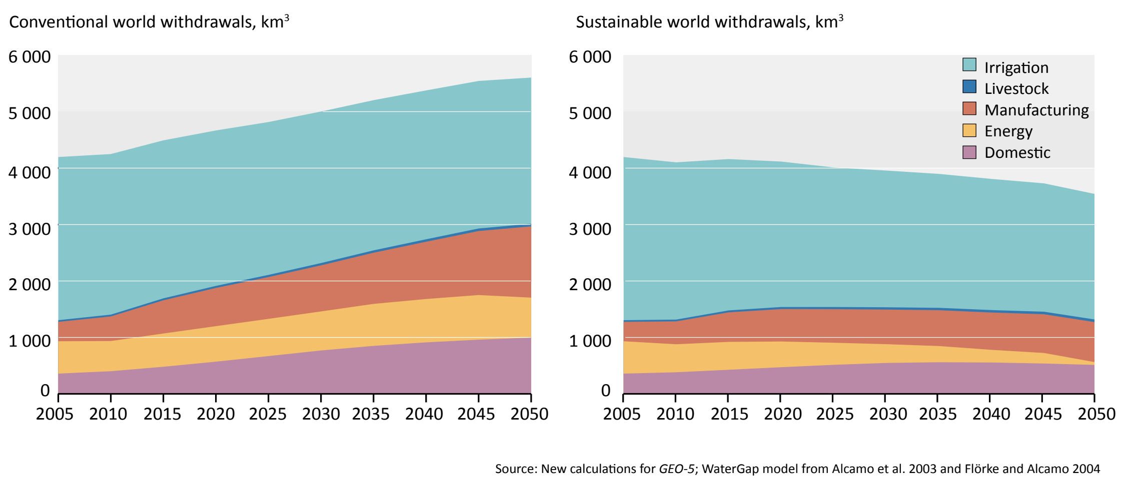
Resource use and resource efficiency in the future

In its GEO-5 publication, United Nations Environment Programme (UN Environment) compared and contrasted two different possible world scenarios ("conventional world" and "sustainable world") across a range of environmental and resource issues. Under the conventional world scenario, current trends were projected to 2050. On the other hand, the sustainable world scenario envisages radical increases in resource efficiency and productivity, with no reduction in economic output.

For example, under the "conventional" projections, water stress could affect 3.9 billion people by 2050 (UN Environment, 2012b, p. 437), leaving many without secure access to safe drinking water and sanitation. While levels of water stress even in "sustainable" scenarios remain significant, greater resource efficiency means that the proportion of the global population without access to safe drinking water in 2050 could fall to 3–5 percent (from 23 percent in 2000) and without access to sanitation to 15–18 percent (from 51 percent in 2000). Figure 7 shows the different projected water withdrawals under these different scenarios.

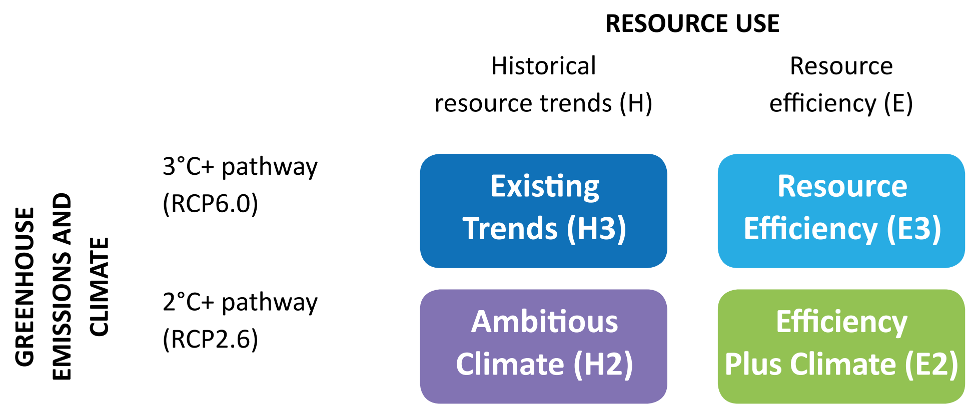
A number of scenarios of resource efficiency and climate change mitigation were newly modelled for this report. They offer overall quantitative insights into the resource, greenhouse gas and economic outcomes from climate policy, resource efficiency policy, and a scenario that included both kinds of policy, as shown in Figure 8. The Existing Trends scenario is calibrated to historical trends in per capita resource use, across major world regions, accounting for changes in income and GDP per capita. The Resource Efficiency scenario assumes the same climate pathway as that of Existing Trends, but introduces a package of innovations, information, pricing incentives and regulations to promote ambitious but achievable improvements in resource efficiency, while compensating for the tendency for such improvements to induce a "rebound effect". The Ambitious Climate scenario assumes resource usage that is line with historical trends, but that the world shifts decisively to a 2°C climate pathway, involving more ambitious emissions reductions from 2020. Lastly, the Efficiency Plus Climate scenario combines the settings for the Resource Efficiency and Ambitious Climate scenarios to explore potential policy interactions.

Figure 7: Projections of water withdrawals by sector under different scenarios



Source: UN Environment (2012b), Figure 16.11, p. 437.

Figure 8: Scenarios for assessing resource and climate futures



Source: Project team.

The Existing Trends scenario projects that natural resource use will increase from 85 billion to 186 billion tonnes over the next 35 years to 2050, reflecting a 28 percent increase in population size and a 71 percent increase in per capita resource use. Modelling resource efficiency and ambitious climate policies and initiatives against this background suggests that they could:

- reduce natural resource use globally by 28 percent in 2050, in combination with ambitious global action on climate change, and stabilize per capita resource use at current levels in G7 countries
- reduce greenhouse gas emissions by up to 20 percent in 2050 (for a given set of greenhouse policies), with global emissions falling to 63 percent below 2015 levels and G7 emissions falling to 74 percent below 2015 levels by 2050, in combination with ambitious greenhouse gas abatement policies
- more than offset the economic costs of ambitious climate action, so that income and economic growth are slightly higher than in the Existing Trends scenario
- deliver annual economic benefits of more than US$2 trillion globally in 2050 relative to Existing Trends, including benefits of US$600 billion in G7 nations, while also helping put the world on track to limit climate change to 2°C or lower.

Moreover, these benefits are delivered compared to an Existing Trends baseline that does not assume significant bottlenecks and disruptions from resource supply failing to meet rising resource demand in a timely way, or significant damage from unabated climate change, biodiversity loss or other environmental impacts. These issues all pose very serious risks to the sustained continuation of economic growth and development, and improvements in human well-being. Given the need to mitigate these risks, the arguments for policymakers to seek step-changes in resource efficiency and productivity are truly compelling.

PART I: RATIONALE AND CORE TERMS

Note: This scientific assessment report on resource efficiency has been produced by the UN Environment's International Resource Panel in response to a commission in June 2015 by the German Government, as an outcome of the G7 Summit meeting in Schloss Elmau. The report is based on the core work of the International Resource Panel, and of other international organizations, in this area. A Summary for Policymakers of this report has also been produced (UN Environment, 2016d). Further details on the commissioning process and the mandate for the report are provided in Part I - Section 1.3.

2015 was a landmark year, due to the signing of two agreements that confirm the international community's shared commitment to achieving equitable and sustainable human development. The 2030 Agenda for Sustainable Development, with its 17 SDGs, is the most complete expression of the aspirations for global human development up till 2030. Furthermore, the Paris Agreement at the 21st Conference of the Parties (COP21) to the United Nations Framework Convention on Climate Change (UNFCCC) saw 195 countries pledge to keep global temperature rise to less than 2°C above pre-industrial levels.

Both of these agreements are highly significant in that they underline the shared commitment of the entire international community – industrialized, emerging and developing economies – to the long-term protection of Earth's resources and ecosystems for the benefit of future generations. At the core of both agreements is the acknowledgement of the need for the sustainable and equitable management and use of Earth's natural resource base, in order to enable poverty eradication and human development for both current and future generations.

This is a report on the prospects for resource efficiency. It considers how resource efficiency can contribute to economic growth, while at the same time reducing the world's use of both materials and energy, and the related environmental impacts.

This first part of the report sets out the rationale for resource efficiency and explains the core terms.

1. RESOURCE EFFICIENCY: BASIC CONSIDERATIONS

1.1. Introduction

Resources — both energy and materials, renewable and non-renewable, and water and land — are fundamental to human wealth creation, development, health and well-being. While Earth provides plentiful natural resources, human populations use them abundantly. In 2015, 84 billion tonnes of materials were extracted by the human economy (UN Environment, 2016a). Thirty-three percent of land on Earth is now cultivated to meet human needs and wants (UN Environment, 2014a, FAO, 2016a). Globally in 2005, humans consumed 25 percent of the biomass produced on land in that year (Haberl et al., 2014, Krausmann et al., 2013). Furthermore, in 2013, 58 percent of fish stocks were fully fished, while 31 percent of fish stocks were estimated to be "fished at a biologically unsustainable level and therefore overfished" (FAO, 2016b). In many parts of the world, freshwater supplies are stressed or scarce (WWAP, 2015).

Human activity is changing ecosystems rapidly and extensively, largely in response to increasing demands for food, fresh water, timber, fibre, minerals and fuel (UN Environment, 2012b, MEA, 2005). These changes have depleted many ecosystem services, increased risks of sudden and disruptive environmental change, and exacerbated poverty among some population groups (MEA, 2005).

In addition, the world population is projected to reach 9.7 billion by 2050 — a 33 percent increase on 2015. Much of this population growth is likely to be concentrated in urban regions of Africa and Asia (UN, 2015c). This increase, coupled with continued economic growth following a "business-as-usual" mode, is likely to dramatically increase pressures on the environment and demand for resources (UN Environment, 2012b, Krausmann et al., 2009). For example, in a business-as-usual scenario, global material extraction is projected to reach 100 billion tonnes by 2030 (OECD, 2015b). This increases to more than 180 billion tonnes by 2050 (Schandl et al., 2015) – more than double current levels. Demand for food and fibre could increase by 60 percent and 80-95 percent respectively by 2050 (FAO, 2012d), while demand for water could increase by 55 percent over the same period (OECD, 2012b). Bulk metals such as iron, copper and aluminium play critical roles in providing large-scale infrastructure, and

elements such as indium, platinum, rhodium and neodymium, though extracted in smaller quantities, will be increasingly critical to efforts to reduce carbon emissions due to their roles in low-carbon technologies such as solar photovoltaic cells, batteries, catalysts and wind turbines (UN Environment, 2010, UN Environment, 2013c, UN Environment, 2013b, BMUB, 2015). Meanwhile, nitrogen and phosphorus are crucial inputs to land for the production of biomass (UN Environment, 2014a, BMUB, 2015). Naturally occurring reserves of such ores and minerals are nonetheless finite, and many are geographically concentrated (UN Environment, 2015d). They can, however, be recovered to differing extents from material flows and waste streams through appropriate recycling strategies. Meanwhile, biomass has a limited rate of renewal, which limits its sustainable consumption.

Earth's capacity to continue to provide resources for human populations in the immediate and more distant future is of critical importance. This was recognized more than 50 years ago in the ground-breaking report *Scarcity and Growth*, from Resources for the Future (Barnett and Morse, 1965). The report concluded that innovation and technology had largely stabilized or reduced the costs of resources, but that environmental endowments were not as amenable to such innovation. It warned that environmental scarcity would ensue if the environmental market externalities were not efficiently internalized.

Environmental scarcity from not internalizing negative environmental externalities over the last 50 years is now all too evident. One of the main messages of the UN Environment GEO-5 report was that environmental systems were being pushed "to destabilizing limits" (UN Environment 2012b, p. 4). With regard to resources, both population and economic growth over the last half-century require Barnett and Morse's conclusions on resource scarcity to be reassessed. The evidence in this report suggests that, in order to avoid dangerously depleting Earth's resources, mankind must employ technological and social innovation more appropriately to enable it to use these resources much more efficiently.

This report examines the prospects for resource efficiency to contribute to economic growth and development while simultaneously reducing the throughput of materials and energy in the global economy, and the resulting environmental impacts.

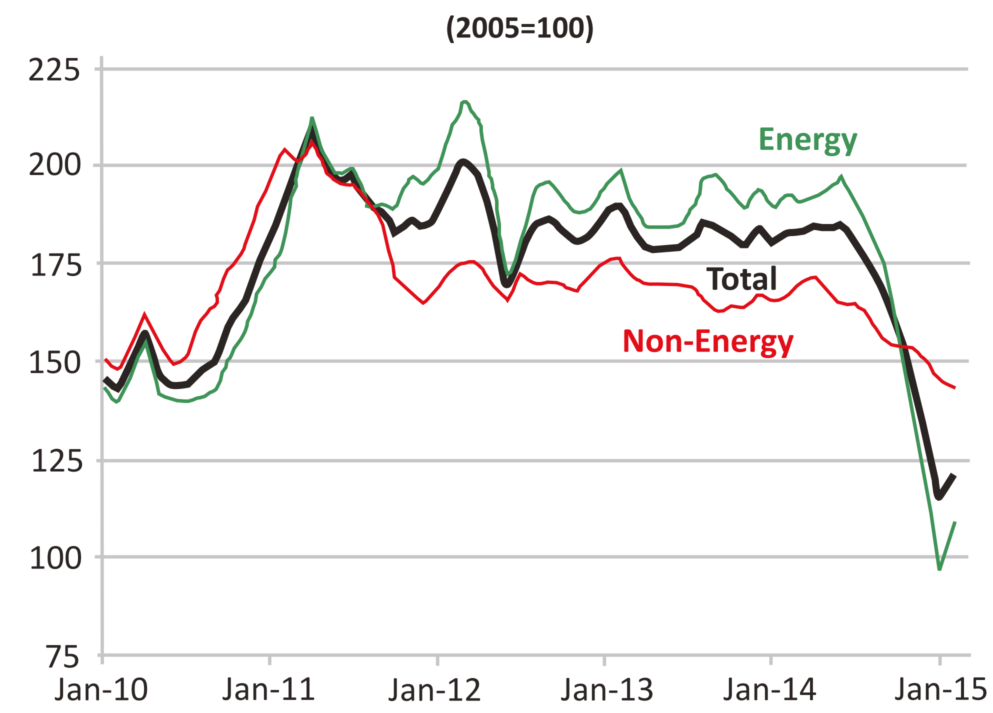
1.2. Rationale for resource efficiency

There are five main reasons why countries may wish to pursue resource efficiency. Namely: to ensure resource availability, minimize resource price volatility, to minimize potential price increases, to limit environmental damage from resource use, and for economic benefit.

The first reason for resource efficiency is to assure the availability of resources for the future Human populations are still growing, as are their economies. Current trends suggest that a growing global population with rising average incomes will continue to drive up the consumption and use of material resources. There are real doubts about the ability of the global economy to ensure the smooth and timely mobilization and supply of the 180 billion tonnes of resources that projections on current trends suggest may be required year after year. The issue is not so much the physical availability of these resources, but rather the scale of the investment required to produce them, the market dynamics that determine investment decisions, and the declining quality of the sources from which materials, particularly metals, need to be extracted. Resource efficiency may be able to reduce — or at least slow the progression of — the demand for materials, thereby reducing the investment required in resource extraction. Once extracted, the recycling of such materials can reduce the risks and threats of serious disruption to their future availability.

The second rationale for resource efficiency relates to the market dynamics arising from the supply of finite and geographically concentrated resources and commodities, and their highly

Figure 9: IMF commodity price indices, 2010–2015



Source: https://www.imf.org/external/np/res/commod/index.aspx volatile prices over time (UN Environment, 2015d, and see Figure 9 for commodity price movements over 2010–2015). Such volatility is disruptive to the economies of both resource-importing and resource-exporting countries. If resource efficiency can reduce the demand for resources, then it may be able to dampen the impacts of this volatility.

The third reason relates to high resource prices. There is evidence that the long, slow decline in resource and commodity prices that characterized the twentieth century has now come to an end. Commodity price indices increased steadily from 2000 to 2012 (Dobbs et al. 2013, Exhibit 1, p. 6) before, led by oil and gas, declining precipitately in 2014–15 (Figure 9), as further evidence of the volatility of commodity markets. However, fossil fuels are a special case, given the global community's intention to move towards low-carbon energy sources. It therefore seems likely that the twin pressures of population and economic growth will soon restore demand for many commodities, setting their prices on an upward trajectory once again. For resource-importing countries, this is likely to have a negative economic impact, although resource efficiency has the potential to increase resource security in these regions. Meanwhile, resource-exporting countries are challenged to turn large windfall gains from higher resource prices into long-term human development outcomes.

The fourth reason relates to limiting the environmental impact of resource extraction and use. Mobilizing billions of tonnes of raw materials each year has serious environmental effects, including pollution, the depletion of renewable resource stocks, land degradation and the loss of biodiversity. Further damage can arise from resource use: most notably, pollution caused by combusting fossil fuels, including carbon emissions that are the principal cause of climate change. In addition, waste disposal has the potential to cause further environmental damage when a product reaches the end of its life. Resource efficiency therefore has the potential to reduce many kinds of environmental damage.

Finally, it seems that there are considerable opportunities to increase resource efficiency with negative net costs, i.e. providing overall economic benefits. Moreover, striving for greater resource efficiency may encourage cost-saving innovation which would otherwise not have occurred, leading to further economic benefits. Clearly the potential for this depends heavily on the prices of the resources concerned, and at times of low prices there are fewer opportunities for cost-effective resource efficiency measures than when prices are higher. Yet even when resource efficiency measures are not strictly cost-effective in market terms, they can present opportunities to reduce firms' and countries' vulnerability to price volatility, and may provide ways to achieve environmental improvements at lower cost than through other means.

These are compelling reasons for taking the idea of resource efficiency seriously and exploring the opportunities for it in the world today in more depth. These reasons explain the increasing interest from governments and other policymakers in this area, and the large volume of literature on this subject that has been produced in recent years, upon which this report seeks to build. Indeed, they explain why the G7 governments have commissioned this report.

1.3. Scope, objectives and limitations of this report

This report examines the potential for increasing resource efficiency in industrialized countries, including the G7, emerging economies and developing countries. It focuses on the use of natural resources and the environment, including energy, land, water, raw materials: biotic and abiotic, marine and freshwater, oceanic and terrestrial. The evidence base includes the recent and ongoing work of the International Resource Panel, as well as that of a number of international organizations that have addressed this issue. The report also seeks to identify transboundary effects and discusses the implications of increasing resource efficiency for economic activity, human well-being and development,

both today and in the future. The methodology employed involved a mixture of desk research, case study analysis, and modelling. Given the size of the relevant evidence base, and the limited time in which to produce the report, it is best described as an illustrative rather than comprehensive report.

This report was commissioned from the International Resource Panel by the G7 group of nations in a communiqué published in June 2015, during Germany's G7 presidency (G7, 2015). This communiqué invited the International Resource Panel "to prepare a synthesis report highlighting the most promising potentials and solutions for resource efficiency in industrialized countries as well as in emerging market economies and developing countries".

As the main objective of this report is therefore to highlight "promising potentials and solutions for resource efficiency", the bulk of the report is devoted to identifying practical and real-world examples of successful improvements in resource efficiency, as well as examples where barriers to improving resource efficiency have been experienced. The report thus sets out the main regional differences in trends of resource efficiency and productivity in recent years, and identifies current and emerging opportunities for increasing these objectives in different regional contexts. There is also some assessment of the potential of these opportunities to help realize the targets underlying the SDGs and to impact the global economy and the economic prospects of various countries and regions. In addition, potential constraints on realizing increased resource efficiency are identified.

In order to establish the background case for resource efficiency, the environmental impacts of resource use, and how they may be reduced by increasing resource efficiency, are discussed throughout the report. The environmental and resource-scarcity problems that may arise from a failure to improve resource efficiency are also considered. However, as even a synthesis of other works on the environmental impacts of resource use (including interactions between environmental impacts across different resources and biophysical systems) would be a huge task, it has not been attempted here. Interactions and synergies between resources, and between environmental impacts—often referred to as "nexus" issues—are highlighted as they emerge naturally from discussions on resources and, in particular, the promising potentials and solutions for resource efficiency. However, in order to reflect the wording of the commission, the "nexus" is not deployed as an over-arching integrating concept.

The G7 communiqué also specified how the report should be produced, and what it should take into account. As already noted, rather than commissioning original research, the G7 asked for a "synthesis report", which "should build upon the existing work and main findings of the International Resource Panel and other relevant international organizations, such as the OECD and UNEP, and take into account relevant international processes such as the 10-Year Framework of Programmes on Sustainable Consumption and Production" (G7, 2015).

Again, the bulk of the report reflects this request and constitutes a synthesis of existing work. This prominently includes, but is not limited to, the work and findings of the organizations and processes mentioned in the above section from the G7 communiqué. In the main, therefore, this report does not present new and previously unreported findings. Its treatment and offering of specific topics and issues is not more detailed, or more novel, than the existing work to which it refers. Indeed, very often the interested reader will need to return to the original, referenced work to appreciate fully what is only summarized in this report. However, the report does contain some new and previously unreported work, in the form of the results of a modelling exercise specifically commissioned for the report, presented in Part IV - Chapter 2.

A further important aspect of the wording of the commission was that policy recommendations

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

were not included within the scope. Instead, the communiqué further invited "the OECD to develop policy guidance supplementing the synthesis report". With policy guidance being considered separately in a companion report from the OECD (2016), detailed policy, analysis and recommendations were deemed to be beyond the scope of the current report. Nevertheless, some discussion of policy inevitably arises in the consideration of "promising potentials and solutions for resource efficiency", to which this report is mainly devoted.

The G7 commission further specified that a report should be available at the 2016 G7 Environmental Ministers Meeting in Japan. For this meeting a Summary for Policymakers of this report was produced (UN Environment, 2016d). While the Summary for Policymakers is consistent with this report, its structure and framing are different, reflecting the fact that the Summary for Policymakers was specifically intended for policymakers. This longer report evolved over a longer period and in response to peer review.

1.4. Structure of this report

Part I - Chapter 2 of this report defines the various terms used to describe the broad concept of resource efficiency. As the use of this terminology to date has been somewhat confusing, this chapter seeks to clarify not only the meaning of the terms used in this report, but also how they are measured. Agreement on and consistent use of these metrics is crucial if the phrase "increasing resource efficiency" is to have quantitative as well as qualitative meaning.

Part II - Chapters 1 and 2 use the new International Resource Panel database on resource and material flows to present global trends in resource use, in resource efficiency and in the "decoupling" of resource use and associated environmental impacts from the monetary growth of the economy. The chapters conclude that much greater rates of increase in resource efficiency than have been achieved historically will be required to prevent unsustainable levels of growth of resource use in the future.

Part II - Chapter 3 briefly sets out the economics of resource efficiency, based on a number of assessments that suggest that increased resource efficiency can contribute to increased competitiveness, economic growth and employment.

Part II - Chapter 4 discusses existing practices in resource use governance and their implications for resource efficiency. The forces that drive the extraction and use of resources for the economy derive from a complex mixture, which varies by country, of market and state interactions. The nature of these interactions determines not only the type and quantities of resources that are extracted and used, but also the related beneficiaries.

Part III - Chapters 1 to 7 explore the potential and practical opportunities for resource efficiency. Chapter 1 describes the objectives and a number of case studies related to the 10-Year Framework of Programmes on Sustainable Consumption and Production Patterns (10YFP). This major global programme, with resource efficiency at its heart, is oriented towards achievement of the SDGs. Chapters 2 to 7 document the potential increases in resource efficiency in some of the social and economic systems and processes that are most connected to resource use: materials and waste management, urbanization, food systems, transport and mobility, power generation, land, water and industrial processes.

Part IV - Chapters 1 and 2 look forward, projecting the trends identified in the previous chapters into the future. They identify how these trends may be altered by implementing some of the opportunities for resource efficiency that previous chapters have shown to be available.

Finally Part V - Chapter 1 draws some conclusions about the potential of resource efficiency

to address the aforementioned challenges, which has caused it to rise up the agenda of G7 policymakers.

2. DEFINITIONS AND METRICS

2.1. Introduction

The terms resource (or eco-) productivity, resource or environmental efficiency, resource intensity and eco-efficiency have all been used to describe how "effectively" economic activities convert natural resources into useful material products or economic output (EEA, 1999) and reduce the associated impacts on the environment. However, the precise definition and measurement of the "effectiveness" of resource conversion, and the scale of the impacts, varies somewhat between each of these terms. Despite being increasingly widely used, these and other related terms and concepts are often deployed rather indiscriminately and interchangeably.

While the diverse application of terms to assess the natural resource impacts of economic activity is encouraging, it is becoming increasingly obvious that these terms are used to cover many different measures and practices, which can cause confusion.[1] A recent study for the European Parliament noted: "As a relatively new concept on the political agenda, there seems to be some confusion as well as different understandings ... about what resource efficiency means" (EP, 2012, p. 9). As the principles underlying these terms become more important, and related practices spread, involving more and more disciplines and practitioners, the lack of clear-cut definitions is likely to give rise to more confusion and cross-purpose communications. The aim of this chapter is therefore to establish a clear framework of a minimum number of functional terms that refer to the effectiveness or efficiency with which humans use natural resources. These terms can then be used consistently in the remainder of the report.

The differences between the terms and metrics in this area can be understood as relating to three key dimensions of the activity in question, along which the effectiveness or efficiency of resource use can be measured. These are economic value or economic output; physical resource use or physical output; and environmental impacts. These and other aspects of the activity then contribute to its overall effect on human well-being. The various terms and metrics used to describe the natural resource and environmental impacts of economic activities typically differ not only in relation to which impacts are being considered, but also to how each of these dimensions is being combined to produce a metric. This chapter refers, therefore, to these three dimensions in setting out the differences between the various metrics.

Eco-efficiency, the earliest of these terms to be used, was first introduced to describe the broad management objective of breaking the link between economic activity on the one hand and natural resource use and negative environmental impacts on the other (Schmidheiny, 1992). This "decoupling" concept is discussed further below. In the following years, eco-efficiency was the subject of considerable discussion and analysis (see, for example, DeSimone and Popoff (1997), where it was defined as relating to "activities that create economic value while continuously reducing ecological impact and the use of natural resources" [p.xix]). This definition notably includes all three of the key dimensions of economic value or output, physical resource use and environmental impact.

By 2000, the World Business Council for Sustainable Development (WBCSD) stated that: "Eco-efficiency is achieved by the delivery of competitively-priced goods and services that satisfy human needs and bring quality of life,

1 For example, the UN Environment Cleaner Production website (http://www.uneptie.org/pc/cp/understanding_cp/related_concepts.htm) gives a brief overview of some of these terms, but does not distinguish rigorously between them. In another source, resource efficiency is interpreted as a measure of resource productivity (PIU, 2001).

while progressively reducing ecological impacts and resource intensity throughout the life cycle to a level at least in line with the earth's estimated carrying capacity" (WBCSD, 2000) (p. 7). The source goes on to describe seven "elements for eco-efficiency improvement": (a) a reduction in the material intensity of goods or services; (b) a reduction in the energy intensity of goods or services; (c) reduced dispersion of toxic substances; (d) enhanced recyclability; (e) maximized use of renewables; (f) extended product life; and (g) increased service intensity of goods and services.

The inclusion of quality of life in the WBCSD's description of eco-efficiency acknowledges that human uses of resources and the environment affect human well-being. This is in contrast to the earlier definition, which included only considerations of economic value and output.

Subsequent terms such as resource productivity, resource efficiency and environmental efficiency have each taken a slightly different emphasis in terms of which of these three key dimensions they are primarily measuring. For example, in its Roadmap to a Resource Efficient Europe, the European Commission defined resource efficiency as "a way to deliver more with less. It increases aggregate economic value through more productive use of resources over their life cycle. It requires using those resources in a sustainable way, within the planet's long-term boundaries. This includes minimising impacts of one resource's use on other resources, including the environment" (EC, 2011a, p. 9).

In order to introduce some clarity and consistency into the terminology of the indicators used in this field, and referred to in this report, this chapter sets out definitions of the different terms and concepts. First, it defines some key underpinning concepts – resources, natural resources and environmental indicators. The chapter then builds on this base to distinguish between the different metrics of resource and environmental efficiency (for example, resource productivity, resource intensity and emissions intensity) on the one hand, and economic efficiency on the other. All of these metrics are in essence ratios of two variables; the different ratios measured by these various concepts, and in particular whether their numerators and denominators are in monetary or physical units, will be set out within each section.[2]

2.2. Underpinning concepts: resources, natural resources and environmental indicators

In EC (2011a, p. 9), resources are defined as "all the resources that are inputs into our economy - metals, minerals, fuels, fish, timber, water, soil, clean air, biomass, biodiversity and land and sea." Resources are therefore aspects of the natural world that have the capacity to produce goods and services that contribute to human welfare. They include air (the atmosphere), water (marine and fresh) and land. Land consists of terrestrial space (for human habitation or the habitats of other species), which in conjunction with soil produces biomass and biodiversity. Sub-soil resources include metal ores, non-metallic minerals, and fossil fuels. Combustion of fossil fuels is a major source of increases in atmospheric carbon dioxide, the principal greenhouse gas (GHG). Ambient energy (for example, solar or wind energy) is another important resource. It should be noted that "natural resources" denotes those provided by nature prior to their extraction or processing by humans (e.g. metal ores, rather than metals), which often requires human labour and manufactured capital.

Material resources are often divided into four major categories: fossil fuels, biomass, metals, and non-metallic minerals. Water is also often included as a resource. Resources, or resource use, may be measured in two ways: with a physical unit, such as mass, length, area or

2 The discussion below is adapted from Dahlström & Ekins (2005).

volume (often thought of as their natural unit); or in terms of their economic value, as discussed below. The quantities of material resources are usually measured in tonnes, through a technique called Material Flow Analysis (MFA), briefly described with some of its key related terms in Box 1. Land is usually measured by its area (e.g. square metres) and water by its volume (e.g. cubic metres). Resource use is usually associated with a certain period of time, often a year.

Environmental indicators fall into two broad categories: those that measure pressures on the environment (for example, emissions to air, land and water, or rate of loss of a certain habitat), and those that measure the state of the environment (for example, air, soil or water quality, or the number of species in the habitat). These physical indicators may also include a time element to show the rate at which the pressure is increasing or the state is changing. Although environmental indicators are sometimes linked to reference values (acceptable or "sustainable" levels), this tends not to be the case for resource indicators, except those for renewable resources.

Resource and environmental indicators at the national level may refer to resource use or environmental outcomes occurring only in the territory under consideration (for example, greenhouse gas emissions originating from the territory, called territorial emissions), or may refer to outcomes also occurring in other territories due to the production of imports. Where the indicators refer to the full resource and environmental outcomes related to consumption in the territory in question, they are often called "consumption-based" indicators or "footprints". The four main calculated footprints are those for land (which includes the land required for the production of biomass), water, materials (metals and minerals) and carbon dioxide. Thus, carbon footprints are related to emissions that are driven by the consumption activities in the country under consideration, irrespective of where these emissions actually take place. The distinction between territorial and consumption (or footprint) indicators is explored in detail, with many examples, in UN Environment (2015d). When calculating efficiency, it is obviously very important to clarify whether the efficiency refers to the direct resource use or environmental impact in the country concerned, or to the wider footprint, which also takes upstream supply-chain impacts into account.

Box 1: Material flow analysis and definitions of its key related terms used in this report

Material flow analysis (MFA) is a technique used to measure the physical weight of materials that flow through or are used by an economy in a certain period of time (usually a year). These material flows comprise the extraction of materials inside the economy and physical imports and exports. Air and water are generally excluded.

Domestic extraction (DE) is the physical weight of raw materials (excluding water and air) extracted from the natural environment for use in the economy.

Physical imports are the imports into the economy, in physical weight.

Physical exports are the exports from the economy into other economies, in physical weight.

Direct material input (DMI) is the input of materials for use in an economy, i.e. all materials that are of economic value and available for use in production and consumption activities.

Domestic material consumption (DMC) measures the total amount of materials used by an economy. It is defined as the quantity of raw materials extracted from the domestic territory, plus all physical imports minus all physical exports.

Direct material input = Domestic extraction + Physical imports

Domestic material consumption = Domestic extraction + Physical imports - Physical exports = Direct material input - Physical exports

The simple weight of traded goods provides an incomplete picture as it does not take into account the raw materials originally necessary to produce these traded goods. **Raw material equivalents (RME)** therefore measures the amounts of raw materials required to provide the respective traded goods. For finished and semi-finished products in particular, imports and exports in RME are much higher than their corresponding physical weight.

Imports in RME are the amount of raw materials required to produce the goods imported into the economy.

Exports in RME are the amount of raw materials required to produce the goods exported from the economy.

Raw material input (RMI) is the amount of raw materials required to produce the goods that are available for use in the economy's production and consumption activities.

Raw material consumption (RMC) measures the total amount of raw materials required to produce the goods used by the economy (also called "material footprint").

Raw material input = Domestic extraction + Imports in RME

Raw material consumption = Domestic extraction + Imports in RME - Exports in RME = Raw material input - Exports in RME

Source: http://ec.europa.eu/eurostat/statistics-explained/index.php/Glossary:Material_flow_indicators

2.3. Definitions of widely used metrics of natural resource use

As discussed, the terms eco-efficiency, resource efficiency and resource productivity have all been used to describe rather broad approaches to the relationship between economic value or output, physical resource use and environmental impact. Building on these underpinning concepts, this section precisely defines the various metrics that have been employed to describe the effectiveness of converting natural resources to material products or economic output.

2.3.1. Technical efficiency

One measure of resource efficiency is the extent to which resource inputs are converted into useful resource outputs. At its most basic, this sort of efficiency may be defined as a ratio of two resource variables of the same kind, i.e. the ratio is dimensionless. For example, material efficiency is measured as a ratio between useful material output, M_o, and total material input, M_i:

$$M_o/M_i = \text{material efficiency}$$

Similarly, energy efficiency is useful energy output, E_o, per input of energy, E_i:

$$E_o/E_i = \text{energy efficiency}$$

With such definitions, efficiencies are less than 1, and are often expressed in terms of percentages (less than 100 percent).

However, efficiency — still conceived as a desirable output per unit of input — may sometimes be measured in different units. For example, the fuel efficiency of a vehicle may be expressed as kilometres per litre of fuel (km/l) or, for a fleet of vehicles, vehicle-kilometres per litre of fuel (vkm/l). Such a concept of efficiency may also be applied to environmental impacts, normally based on emissions. Thus the environmental efficiency of a motor vehicle may be expressed as kilometres per unit of emissions (for example, km/gCO_2). However, it is more usual to express such relations as *intensities*, as discussed further below.

As these definitions are consistent with the definition of efficiency used in engineering, they are here called *technical efficiency*.

2.3.2. Resource productivity

Productivity is a term used in relation to the production of economic output (normally measured in monetary terms) by an input. Hence material and energy productivity are the economic output, Yo, per unit of natural resource input, M_i:

$$Y_o/M_i = \text{material productivity,}$$

and the economic output, Yo, per input of energy, E_i:

$$Y_o/E_i = \text{energy productivity}$$

This definition of resource productivity has been advocated as a measure of the effectiveness with which the economy as a whole, or a particular economic sector or firm, generates added value from the use of natural resources. It can therefore be used to determine the extent to which corporate, sectoral or national economic growth is linked to resource use (PIU, 2001). If, for example, Y_o/M_i in a particular year is normalized to be 100, then if in a future year the ratio is greater than 100, the physical input will have grown at a slower pace than the economic output. This situation, known as decoupling, is further discussed below.

Choosing specific variables to operationalize the indicator will depend on the unit and purpose of analysis, as well as data availability. To analyse resource productivity trends at the firm level, a range of indicators has been suggested (see for example WBCSD (2000)), while at the sectoral and national levels, the choices are more constrained.

This definition of resource productivity is analogous to the concept of labour productivity, which is measured at the company level as wages (part of value added) per worker, or at the national level as GDP per worker (or per hour worked). The latter is a key indicator of economic productivity at the national level, where L stands for labour:

Y_o/L = labour productivity

However, while productivity as a term is normally associated with an economic output, in a broader sense it can refer to just the production of one (desirable) factor (the numerator) by another factor (the denominator). For example, not only the economic output per worker, but also the useful material output (e.g. number of cars manufactured) per worker, may be of interest:

M_o/L = material productivity of labour

as may the useful material output per input of energy (a key measure of the quality of a metal ore):

M_o/E_i = material productivity of energy

Sometimes, of course, the various indicators might be linked. For example, in mining or smelting one might expect a good quality mine or ore to have a relatively high material productivity of energy (M_o/E_i). Here, M_o is measured in physical terms, implying high relative material output per unit of energy input. This is accompanied by relatively high material efficiency (M_o/M_i), implying relatively low mining waste or furnace slag. However, production from high-quality ores may also be associated with a lower price of the material output, reflecting the lower costs of production. In this case, the material productivity (M_o/E_i, with M_o measured here in monetary terms) and the energy productivity (Y_o/E_i) of the process are relatively low in economic terms.

2.3.3. Resource intensity

As this report defines resource intensity as the inverse of resource productivity, labour intensity would be measured as L/Y_o, energy intensity as E_i/Y_o and material intensity as M_i/Y_o.

2.3.4. Emission intensity

The concept of intensity can also be applied to the production of an undesirable output (solid, liquid or gaseous, often resulting in pollution when emitted to air, land or sea) by another

factor; for example carbon dioxide output, C_o, resulting from the use of energy.

Emission intensity may relate the emissions to either an input factor, or to the desirable output of production. An example of the former is:

C_o/E_i = the carbon (emission) intensity of energy (for example, the energy input into a vehicle)
(which, assuming no abatement of carbon emissions, is the same as the carbon intensity of the energy inputs, C_i/E_i)

An example of the latter is the carbon intensity of electricity, which is usually measured as

C_o/E_o = the carbon (emission) intensity of electricity
(where E_o is the electricity output, rather than the input of primary fuels, which are responsible for the carbon emissions)

Emission intensity may also be considered as the inverse of environmental efficiency. Thus, to continue with the example given earlier, the carbon (emission) intensity of a vehicle may be its CO_2 emissions per km travelled (gCO_2/km).

Intensity may also refer to the emissions, Em_o, per unit of material inputs:

Em_o/M_i = the emission intensity of material inputs

or the emissions, Em_o, per unit of economic output:

Em_o/Y_o = the emission intensity of output

(for carbon emissions, with no carbon abatement, the carbon (emission) intensity of output, C_o/Y_o, is the product of the carbon intensity of the energy inputs and the energy intensity of output, i.e. $C_o/Y_o = C_o/E_i * E_i/Y_o$).

2.3.5. Resource efficiency

The term "resource efficiency" is used in this report to refer generically to all these different ideas: the technical efficiency of resource use; resource productivity, or the extent to which economic value is added to a given quantity of resources; and the extent to which resource extraction or use has negative impacts on the environment (increased resource efficiency implies reducing the environmental pressures that cause such impacts). As noted above, resource intensity is the inverse of resource productivity, while environmental intensity is the environmental pressure per unit of value added.

2.3.6. Economic efficiency

The concept of economic efficiency differs significantly from all the definitions of resource and environmental efficiency, or resource and emission intensity, set out above. First, it describes relationships between economic values, measured in monetary terms and may be used at the firm level to relate economic outputs and inputs, Y_o/Y_i. In contrast to engineering or technical efficiencies, which are always less than 1 (e.g. $M_o < M_i$), for a profitable company $Y_o/Y_i > 1$, with the difference between Y_o and Y_i being the *value added* by the company.

Where the economic inputs are materials, they too will be measured according to their value. This is one reason why economic efficiency at the firm level may be consistent with substantial material inefficiency. The former will depend entirely on the monetary costs of the physical inputs, any associated waste disposal costs, and the costs of the processes used to convert these inputs into useful products. If the costs are minimized (i.e. Y_i is low) by using the material resources inefficiently (i.e. M_o/M_i is low), this may be consistent with high profitability (i.e. maximum Y_o/Y_i). It is therefore by no means unlikely that a market operating solely according to market rules will deliver a resource-inefficient outcome in physical terms.

At the macro level, economic (sometimes called Pareto) efficiency refers to a situation in which resources, expressed in monetary terms, cannot be allocated differently between economic actors to make one actor better off, without making at least one other actor worse off. Again, such economically efficient allocation says nothing at all about the technical or resource efficiency of the allocation.

The conceptual relationship between resource efficiency and costs, at both a micro and a macro level, is discussed further below. It may simply be noted here that economic efficiency may always be improved by the appropriate internalization of external costs (as defined further below) from resource use or its associated environmental impacts.

Box 2 summarizes the discussion of terminology in Part I - Section 2.3. This report will use these key definitions for the various indicators of resource efficiency and related concepts.

Box 2: Summary of terminology for indicators of resource efficiency and related concepts

Technical Efficiency
Ratio of two physical variables, for example, material output, Mo, and material input, Mi; or energy output, Eo, and energy input, Ei; or distance travelled (D, km) and fuel used (F, litres)

Mo/Mi = material efficiency

Eo/Ei = energy efficiency

D/F = fuel efficiency

Technical efficiency may also refer to environmental impacts as well as resource use, for example relating carbon emissions (C) of a mode of transport to the distance travelled:

D/C = carbon efficiency of transport

Resource Productivity
Ratio of two different variables. Numerator measured by an economic welfare indicator, Y, unless otherwise qualified:

Yo/Mi = material productivity

Yo/Ei = energy productivity

Yo/L = labour productivity

or a ratio of any two variables of interest that indicate the production of a (non-economic welfare) numerator by a denominator:

Mo/L = material productivity of labour

Mo/E = material productivity of energy

Resource or Emission Intensity
The inverse of resource productivity, or the production of an undesirable factor by another factor:

Ei/Yo = energy intensity

Co/Ei = the carbon (emission) intensity of energy input

Co/Eo = the carbon (emission) intensity of energy (usually electricity) output

Emo/Yo = the emission intensity of output

Co/Yo = the carbon (emission) intensity of output

2.4. Measuring human well-being

Traditional attempts to measure human welfare have tended to focus on narrow and measurable components such as economic welfare.

Economic welfare is normally measured in monetary terms, and often simply by the level of consumption expenditure. While such concepts might seem intuitively familiar to individuals in the context of their own desires to live a “good”, “happy” or “prosperous” life, such concepts are also notoriously elusive. There are no simple or formulaic answers to questions of how well-being or quality of life can or should be maximized for any individual, or indeed how these notions can be assessed and measured. Accordingly, Clark (2014) notes that human well-being “is difficult to define and even harder to measure”. Clark considers three contrasting approaches to considering human well-being: those that focus on “utility (happiness, desire, fulfilment)”; those that focus on “material well-being (most notably, income and resources)”; and “‘list orientated’ views (needs, rights, capabilities)”. Clark proposes the idea of “sustainable human development”, arguing that “a more comprehensive account of human well-being is required to bridge the gap between mental and physical states and to take note of the environmental and material basis of sustainable well-being” (Clark, 2014). This idea of “sustainable human development” clearly relates to the SDGs, which are referred to throughout this report, and addressed explicitly in Part IV - Chapter 1.

Layard (2005) equates happiness more or less synonymously with human welfare or well-being, arguing that his research shows that human welfare depends mainly on seven issues. These “big seven” — the first five in Layard’s order of importance — are:

- Family relationships (with an emphasis on the importance of marriage)
- Financial situation (with greater importance, above a certain income threshold, being attached to relative rather than absolute incomes)
- Work (currently mainly organized through employment)
- Community and friends (trust)
- Health (especially mental health)
- Personal freedom
- Personal values (with special importance being attached to religious faith)

In a similar vein, Hueting includes: income, employment, working conditions, income distribution, leisure, health, environment and security as key contributors to human welfare. But he also suggests both the environment and income distribution (or inequality), which are conspicuously absent from Layard’s list (Hueting, 1992, p. 257). Environmental issues are central to this report’s main focus on resource and environmental efficiency, while distributional issues are discussed in relation to resource and environmental governance.

There are now a number of indicators that seek to reflect this broadening of the notion of human welfare. Some have approached this in monetary terms, such as the Index of Sustainable Economic Welfare, the Genuine Progress Indicator, and the World Bank’s genuine savings indicator, or through inclusive wealth accounting. Others, including the OECD, have sought to capture the multiple dimensions of human welfare through frameworks of “sustainable development indicators”. These different indicator approaches are described in some detail in Ekins (2012). The most recent globally accepted grouping of sustainable development indicators are the aforementioned SDGs (see UNEP (2015f)) for a discussion of the relationship between the SDGs, natural resources and the environment).

These points are raised to clearly recognize that, despite being intricately related, economic output and human well-being are not one and the same. We agree with the overwhelming majority of policymakers that, other things being equal, human well-being is positively related to income and economic output. We nevertheless

acknowledge that there are other views (one of the best routes into this extensive literature is provided by Jackson (2009)). Therefore, if resource efficiency that eases resource challenges and reduces environmental challenges also contributes to economic growth, it is assumed to be beneficial to human well-being. This is provided that it does not result in negative social impacts on important well-being issues. Whether, and the extent to which, this is the case is an empirical matter. Some of the evidence on the resource efficiencyeconomy interaction is intensively explored in Part II - Chapter 3 and Part IV - Chapter 2. Resource governance is the explicit subject of Part II - Chapter 4, but in general social issues, such as income distribution and employment, are discussed less intensively, as and when they arise throughout the report. This does not reflect their lack of importance, but is simply to avoid further lengthening this report.

2.5. Human preferences

The weight that people attach to the different contributors to human welfare mentioned above is determined by what economists call “human preferences”. In economic analysis, these preferences are often assumed to be taken as given and exogenous, i.e. originating outside the economic system. In fact, they are strongly influenced by human culture and can change over time, albeit often rather slowly. They can also be altered by the course of events or by public policy, although the nature and direction of such change depends on many factors and is hard to predict. Similarly, many policymakers aspire to “change human behaviour” relating to the use of resources and the environment. However, this is difficult to achieve, and perverse and unintended consequences can result from such efforts.

Human preferences about resource use and its environmental impacts, resource and environmental efficiency, and the “waste” of resources are obviously crucial factors affecting the ease with which policymakers will increase resource efficiency. So too are the relative values that people attach to such resource-related issues and the welfare they derive from resource consumption. It is clear that such preferences and values can and do change, but such change tends to take time, is hard to predict, and is by no means easy to influence through public policy.

Throughout this report, and especially in Part III - Chapter 1, reference is made to Sustainable Consumption and Production (SCP). There is widespread recognition, not least in the discourse around SCP, that resource- and environment-intensive consumption patterns will need to change if the resource- and environment-related challenges that they give rise to are to be effectively addressed. Since detailed policy discussion is beyond its scope, this report leaves several questions open: can and will these consumption patterns move in a resource-efficient direction as a result of changes in culture and human preferences? Will policy be required to effect such change? Will such change are achieved through a combination of both policy change and culture and human preferences?

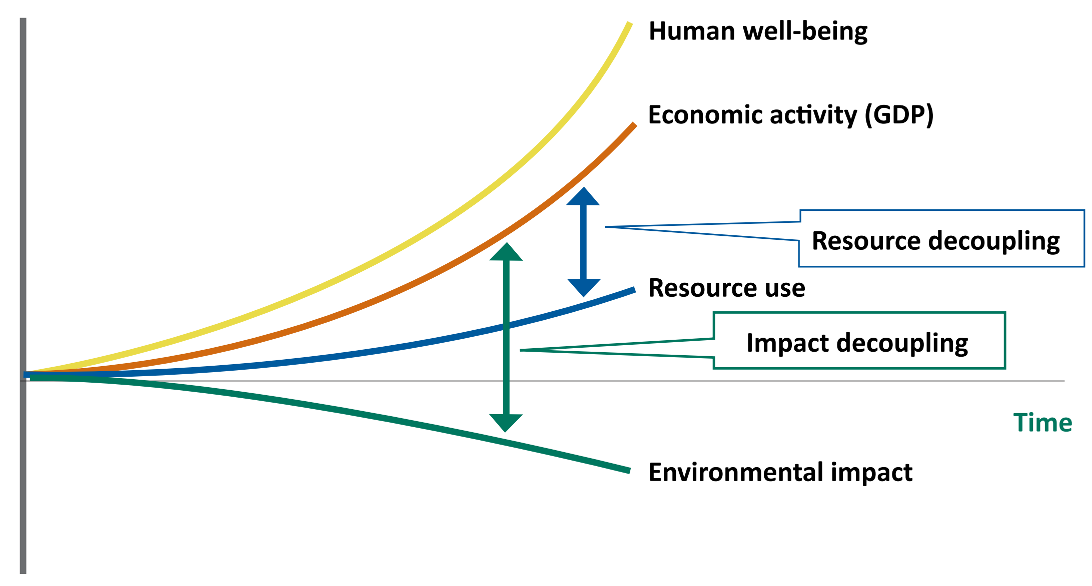
2.6. Decoupling

Decoupling has been a core concept underlying the work of the International Resource Panel more or less since its inception. The term describes a situation in which resource use or an environmental pressure either grows at a slower rate than the economic activity that is causing it (relative decoupling) or declines while the activity continues to grow (absolute decoupling) (UN Environment, 2011b). Increasing human quality of life or well-being (challenging to measure and lacking in consensus, as discussed above), or the value of economic output (more straightforward to measure), while proportionately reducing both resource use (“resource decoupling”) and negative environmental impacts (“impact decoupling”) has been referred to as “double decoupling” (BIO Intelligence Service et al., 2012). The concept of decoupling is represented in Figure 10 (from the International Resource Panel *Decoupling 1* report (UN Environment, 2011b)), which shows the increasing trajectories for GDP and human well-being that may result from the achievement of the SDGs. However, Figure 10 also shows resource use increasing at a much slower rate than GDP (relative resource decoupling) and environmental impacts actually declining (absolute environmental decoupling). This conceptual figure therefore indicates the goal of resource efficiency, through the notion of decoupling: that economic output and human well-being can be allowed to continue to increase, at the same time as rates of increasing resource use and environmental impact are slowed, and in time brought into decline. This would enable resource use and the delivery of ecosystem goods and services to be sustained.

There are, of course, many different resources and many different environmental impacts. These must be specified with some precision in any empirical application of the decoupling concept, together with the period of time under consideration. As an example, UN Environment (2011b) (Figure 2, p.xiv, not shown here) does show relative decoupling between resource use and GDP (as in Figure 10) over the period 1970–2005, but not over 1900–1970.

With regard to environmental pressures, some evidence on decoupling in relation to six different types of air emissions is shown in Table 1. In this table, all the countries (the only ones mentioned in its source) experienced economic growth in the period 1990–2005 (the GDP index in 2005 is greater than 100). Relative decoupling of GDP growth from these air emissions has occurred over this period when the countries’ air emissions index is greater than 100 but below that of their GDP index. Absolute decoupling has occurred when their air emissions index is below 100.

Figure 10: Decoupling of resource use and environmental impacts from GDP growth



Source: UNEP (2011b), Figure 1, p.xiii.

Table 1: GDP and domestically produced emissions indices, selected OECD countries, 2005 (1990=100)

	GDP	SO_x	NO_x	Particulates	CO	VOC	CO_2
France	132	35	66	67	50	52	98
Germany	123	10	50	10	33	35	82
Ireland	258	38	95	106	55	58	126
Japan	120	76	94		67	88	107
Portugal	135	69	104	133	70	94	143
Turkey	173	128	166		92		184
UK	143	19	55	53	29	41	85
USA	155	63	74	81	62	69	116

Shading = no absolute decoupling

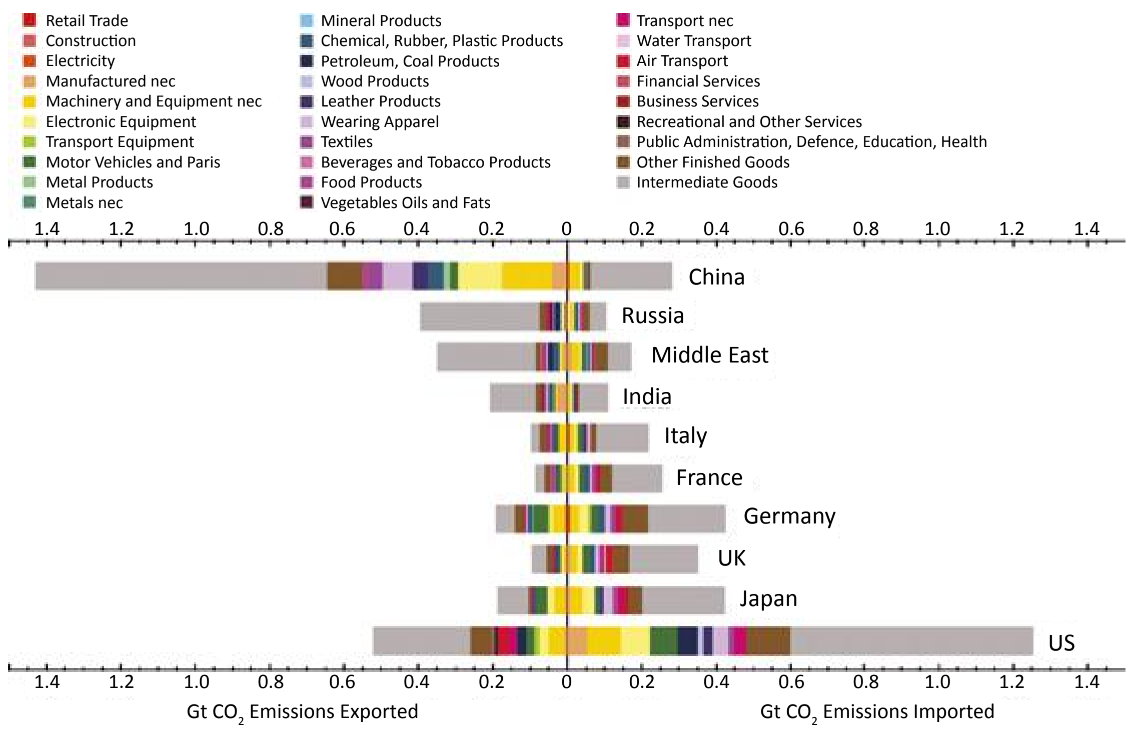
Source: Everett et al. (2010) p. 22.

Five of the air pollutants (all but CO_2) are local. Table 1 shows that absolute decoupling was achieved in all countries for CO (carbon monoxide) and VOC (volatile organic compounds), all but Turkey for sulphur oxides (SOx), all but Portugal and Turkey for nitrogen oxides (NO_x), and all but Portugal and Ireland for particulates. The countries that failed to achieve absolute decoupling for these pollutants at least managed relative decoupling.

However, Table 1 also shows that the story for the greenhouse gas carbon dioxide (CO_2) was much less positive over the same period. Only France, Germany and the UK achieved absolute decoupling, and Portugal and Turkey did not even achieve relative decoupling. Given the importance of fossil energy use to the economy, and the lack to date of cost-effective abatement opportunities for CO_2, it is perhaps not surprising that these emissions are harder to decouple from GDP than the local air emissions.

Table 1 shows only those air emissions that originate from a country's territory (said to be calculated from a territorial perspective). Also of interest are measures that take account of a country's resource use and emissions and other environmental impacts associated with its imports; these measures are said to be calculated from a consumption or global supply-chain perspective. Such measures are important because they can show the extent to which any reduction of impacts or resource use in the country in question has been offset by an increase in impacts or resource use in other countries due to international trade. Figure 11 illustrates how differences between territorial and consumption measures can arise as a

Figure 11: Balance of emissions embodied in imports and exports of the largest net-importing/exporting countries (and Middle East region)



Source: Davis and Caldeira, 2010.

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

result of international trade, in the case of CO_2 emissions. It shows the difference between the CO_2 emissions embodied in imports (included in consumption emissions) and exports (included in production emissions) of the largest net-importing/exporting countries (and the Middle East region). China is very noticeable for having substantially more CO_2 emissions embodied in its exports than in its imports; the US, on the other hand, is noticeable for the opposite, having substantially more CO_2 emissions embodied in its imports than in its exports.

The importing and exporting of CO_2 between national territorial emissions accounts, as a result of international trade, explain the differences between territorial and consumption measures of CO_2 emissions. Both measures are compared for a number of countries and regions in Table 2.[3]

There is a large difference in per capita CO_2 emissions between industrialized countries, ranging from around 20 tonnes per capita in the United States to around 10 tonnes per capita in the EU-25, Japan and Russia. Much lower per capita CO_2 emissions in developing countries reflect a very different standard of living, ranging from two tonnes per capita in India to about six tonnes per capita in China.

A footprint perspective for CO_2 emissions shows that all industrialized countries rely on production and related emissions from abroad

Table 2: Per capita territorial CO_2 emissions and CO_2 footprint of final demand for selected countries and regions, 1990, 2000 and 2007

	Territorial CO_2 emissions (tonnes per capita)			CO_2 footprint of final demand (tonnes per capita)		
	1990	2000	2007	1990	2000	2007
United States	20.75	20.44	20.61	21.16	26.36	25.81
EU-25	9.72	9.27	9.37	11.61	11.55	12.89
Japan	9.71	10.37	10.77	12.93	14.44	13.99
China	2.70	3.27	5.78	2.29	2.75	4.26
India	1.58	1.83	2.05	1.51	1.61	1.73
Indonesia	3.70	4.94	5.81	3.22	3.71	4.66
Russian Federation	13.14	8.09	9.03	11.97	6.11	7.56
South Africa	8.26	7.75	8.42	6.41	6.11	7.38
World	5.31	5.19	5.77	5.30	5.18	5.75

Source: Author calculations; direct CO_2 emissions calculated from the Emission Database for Global Atmospheric Research (EDGAR); CO_2 footprints calculated using the EORA MRIO framework (Lenzen et al., 2013) in the context of Schandl et al., 2016.

3 It should be noted that global emissions are the same whether computed on a production or consumption basis. An increase in one country's consumption emissions will be reflected in a matching reduction in the consumption emissions of the country from which the first country is importing goods and services.

to satisfy their final demand. CO_2 footprints are between 25 and 38 percent higher than direct emissions for the United States, Japan and the EU-25. Despite the low level of direct emissions in developing countries, between 12 percent (South Africa) and 26 percent (China) of their CO_2 emissions are for exports of goods and services. This means that the per capita level of CO_2 that supports consumption in those countries is actually significantly lower than the direct emission accounts would suggest.

Table 3 shows the "headline" and "dashboard" of indicators of resource use proposed by the European Commission in its Roadmap to a Resource Efficient Europe (EC, 2011a, EC, 2011b), covering materials (through the Resource Productivity Headline Indicator), land, water and carbon.

The European Commission advises: "The lead indicator and the dashboard are closely linked and should normally be used in combination. This is because the scope of the lead indicator does not cover all relevant natural resources, it has a national rather than a supply-chain perspective (thus not covering shifts of material use from EU to abroad) and, furthermore, economic value, scarcity and environmental impacts of a resource are only partially correlated to its weight" (EC, 2011b)(p. 66).

Part II - Chapters 1 and 2 show some trends in global resource use in these categories, while Part III - Chapters 1 to 7 explore in more detail how specific measures can be implemented in various sectors to support decoupling. These include generalizable resource hierarchy principles such as "the 3Rs" – reduce, reuse, recycle — the distinctions between which are

Table 3: Indicators of resource use proposed by the European Commission

	Territorial perspective	Consumption/global supply-chain perspective
Headline indicator		
Resource productivity	GDP/Domestic material consumption (DMC)	N/A
Dashboard of indicators		
Land	Artificial land or built-up area (km²) – available with restrictions in time-series	Indirect land use/embodied land for agricultural and forestry products (²) – to be developed
Water	Water exploitation index (WEI, percent) – available with restrictions on completeness of data and regional/temporal resolution (river basin/intra-annual variations)	Water footprint – to be updated and improved or Embodied water – to be developed
Carbon	GHG emissions (t) – available	Carbon footprint – estimates available from scientific sources

Source: adapted from EC (2011b), p. 68.

explored in Part II - Chapter 2, as well as more sector-specific strategies applying to food, transport, water, urban, and other systems.

2.7. Costs

Despite its common use and seemingly intuitive meaning, the word "cost" has a number of different connotations. It is important to be aware of these in the resource efficiency context, because resource efficiency is often presumed to be able to save, or reduce, costs.

2.7.1. Cost as expenditure

The purchase of goods and services involves expenditure, which is often referred to as the cost of the goods and services. For a single good or service, the cost is also called the price of the good or service. The total cost of a purchase is the sum of the quantity of each good and service multiplied by its price. Where the purchase is intended to satisfy an immediate human need or want, it is called consumption expenditure.

2.7.2. Cost as investment

Investment normally also involves expenditure on goods and/or services, but in this case it is envisaged to produce some future return, instead of or in addition to some present satisfaction. For the investment to be considered economically viable, the sum of the future returns over a given period, discounted back to the present through a discount rate, needs to exceed the investment expenditure, as expressed through rates of return and/or payback periods. The economic viability of investment in resource efficiency, or in waste reduction, therefore depends critically on the cost/price of the resources that have been saved, or the cost of the waste disposal that has been avoided. Both these costs are subject to market forces and can be influenced by public policy. Whether investments in resource efficiency will result in cost savings can therefore only be calculated on a case-by-case basis, taking market and policy conditions into account.

2.7.3. External cost

An external cost is a negative impact from an activity (normally an economic activity) on someone who is not involved in the activity, which is not taken into account in the cost of the activity. Many environmental impacts involve external costs, including greenhouse gas emissions which result in negative impacts from climate change, or local air pollution which results in negative health impacts. A recent IMF paper (Coady et al., 2015) (Appendix Table 3, p. 38) estimated the external costs related to climate change and local air pollution from burning fossil fuels in 2015 to be around USD 4 billion.[4] The price/cost of fossil fuels would increase significantly above their market price were these costs to be included in the price, for example through appropriate taxation, as they should be if economic efficiency is to be improved. Here is an example where both environmental and economic efficiency could be improved through the same policy instrument.

2.7.4. Opportunity cost

"Opportunity cost" describes the benefits foregone by using financial or other resources in one way rather than another. In cost-benefit analysis, where a certain quantity of resources can be used for a number of different purposes, the economically efficient choice is the purpose that yields the highest benefit for the given cost. In this case, the opportunity cost of the choice refers to the benefits that would have been delivered by the most beneficial non-selected purpose. The term is relevant to resource efficiency assessments in cases where cost-effective opportunities for resource efficiency are not implemented. This may be because, for the economic actor concerned, other investment opportunities yielded a greater benefit than resource efficiency, and these were therefore implemented instead.

4 This is an estimate of the costs of damage from air pollution, expressed in monetary terms. It is not an actual financial transfer.

2.7.5. Microeconomic cost

Microeconomic costs are the real expenditure that firms, governments or households must make to purchase goods and services. These are the costs that feature in marginal abatement cost curves, or in aggregate cost figures, such as those cited in Part II - Chapter 3. These suggest that resource efficiency may be substantially improved through expenditure that, because of the resource savings that it induces, is in effect negative net costs, i.e. benefits. Costs that result in net benefits are usually called investments, as noted above.

2.7.6. Macroeconomic cost

Due to the complex interlinkages in an economy, microeconomic costs do not sum simply into aggregates that then express macroeconomic costs. The expenditure (i.e. costs) of one economic actor is the income, and may support the employment, of another. Furthermore, expenditure may in fact constitute investments that generate benefits in future time periods, and unemployment may rise or fall, resulting in positive or negative multipliers. Gaining insights into these interactions requires the use of macroeconomic models. Some of the issues raised by such models, and the results they generate, are discussed in Part II - Chapter 3.

2.8. Conclusions

A myriad of other terms have been used in relation to resource efficiency. Some refer to processes or strategies to increase resource efficiency, such as the 3Rs (Reducing waste, Reusing products or components, perhaps through their repair, and Recycling materials. The remanufacture of products and components may also be added to this list). Other concepts, such as the "green economy" and the "circular economy", are broader still. Part II - Chapters 3 and 4 and Part III - Chapter 2 briefly discuss these other terms and concepts, which can be described, at least in part, by one or more of the ratios set out in Box 1. The choice of metric will depend on the concept and the context in which it is being considered. These ratios are therefore the building blocks with which this report will define, compare and analyse the various concepts relating to resource efficiency and eco-efficiency that have emerged in this diverse body of literature.

Photo: ©AFP

PART II: RESOURCE EFFICIENCY: TRENDS, ECONOMICS AND GOVERNANCE

Part II of this report considers trends in resource use and resource efficiency, and the economics and governance issues affecting these concepts. Chapter 1 of this part examines recent trends in resource use, discusses the currently emerging environmental impacts of such trends, and considers the potential challenges that could lie ahead if such trends were to continue unabated. Chapter 2 of this Part II examines recent trends in resource use efficiency, and asks whether the rate of these improvements may be sufficient to avoid environmental impacts. In both of these chapters, four main categories of resources are reviewed: materials, land, water and energy. While both chapters give some consideration to the implications of current trends in terms of future challenges, Part IV of this report provides a more detailed exploration of future trends.

Part II continues by considering in detail the underlying conditions that affect resources use, and the extent to which resource efficiency can be improved: Chapter 3 of Part II considers the economics, and Chapter 4 the governance of resource use and resource efficiency.

1. TRENDS IN RESOURCE USE AND ENVIRONMENTAL IMPACTS

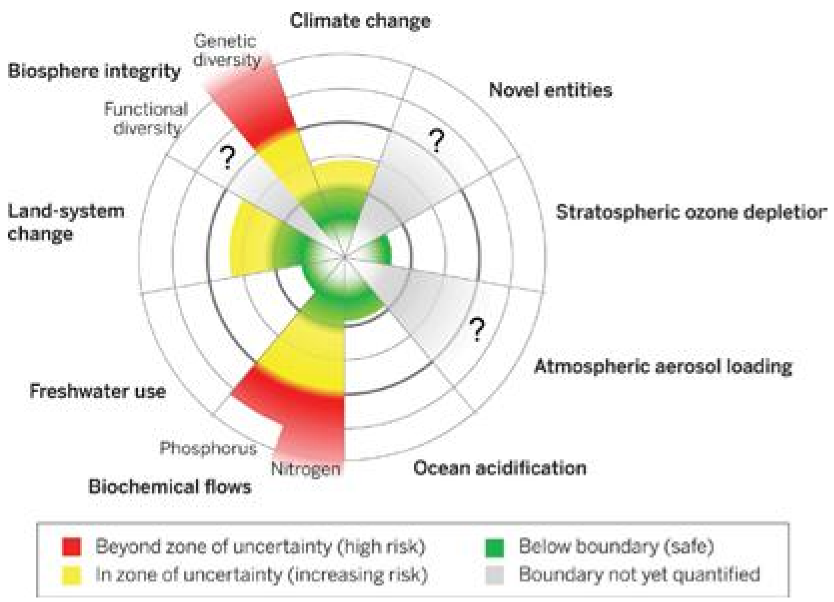
The world economy and its use of resources cause major environmental impacts. These relate to both the large-scale use of resources such as land and water and emissions from the production and consumption of materials and energy.

The IPAT identity is one way of describing these environmental impacts (Commoner, 1972, Ehrlich and Holdren, 1971). This states that environmental impact (I) is a function of the number of people (P), the affluence per person (A), and technology (T). For population and affluence, the relation is strictly positive (other things being equal, higher P and A will lead to higher I). The T variable conceptually encompasses both physical technologies and social institutions, which together determine the scale of resource use and environmental impact. On the one hand, technology has enabled society to access and use resources on an ever-larger scale, with new or more damaging emissions (for example, novel chemicals or radiation), thereby increasing environmental pressure. On the other hand, technology can be used to increase the efficiency of resource use and to develop less polluting alternatives.

It is important to realize that, notwithstanding the important influences of population and affluence on the environment, all environmental impacts actually occur through physical economic activity: the extraction, production and use of resources and products. Such activity (in what is sometimes called the technosphere or anthroposphere) thus forms the interface between society and the environment. Linking the IPAT identity to resource use and resource efficiency aligns it with the concept of “double decoupling” (BIO Intelligence Service et al. (2012)), whereby continuing economic development is decoupled from resource use, while resource use is in turn decoupled from environmental impacts (as discussed in Part I - Section 2.6). This acknowledges the position of the resource use system as the connecting point between the economy and the environment. The P and A factors have been on an upward trajectory since the beginning of the Industrial Revolution, with the population dynamic being hard to change through policy, and affluence being considered desirable. As a result, food, shelter, clothing and various other services are required in increasing quantities worldwide. "Double decoupling" is dependent on a T factor that can allow growth in population (P) and affluence (A), while simultaneously achieving reductions in resource use and environmental impacts.

This is a considerable challenge. There has been a steep increase in both resource use and its environmental impact in the 20th Century. At the same time, industrial production in a number of countries has considerably increased resource productivity, and has largely cleaned up point source emissions; thus considerably reducing environmental impacts (as shown for some countries in Table 1). Nevertheless, as will be discussed in the following sections of this chapter, the overall trend of resource use is upward. Furthermore, notwithstanding the successes in decoupling resource use from some environmental impacts in some countries, on a global scale the environmental pressures arising from the continued growth in resource use also, with few exceptions, continue to grow. Indeed, the challenges have now become so large that scientists have warned that "planetary boundaries" which mark the "safe operating space" for resource use and pollution are close to being crossed, or have already been crossed, for several environmental impact categories (Rockström et al., 2009b, Steffen et al., 2015). As shown in Figure 12, according to the analysis of Steffen et al. (2015), human activities have already left the "safe operating space" in terms of climate change, genetic diversity, land-use system change and biochemical flows.

Figure 12: Current status of the control variables for seven planetary boundaries



Note on Figure: As described by Steffen et al. (2015), "The green zone is the safe operating space, the yellow represents the zone of uncertainty (increasing risk), and the red is a high-risk zone. The planetary boundary itself lies at the intersection of the green and yellow zones. The control variables have been normalized for the zone of uncertainty; the center of the figure therefore does not represent values of 0 for the control variables. The control variable shown for climate change is atmospheric CO_2 concentration. Processes for which global-level boundaries cannot yet be quantified are represented by gray wedges; these are atmospheric aerosol loading, novel entities, and the functional role of biosphere integrity."

Source: Steffen et al.(2015).

The International Resource Panel report "Assessing the environmental impacts of consumption and production: priority products and materials" concluded that the most severe impacts on ecosystems presently originate from habitat loss and land-use change (UN Environment, 2011a). Reflecting the analysis of Steffen et al. (2015), the International Resource Panel finds that climate change has until now had comparatively limited impacts. However, this is expected to change in the future through the steeply upward trend of greenhouse gas (GHG) emissions and resulting atmospheric concentrations. Climate change is expected to have large impacts at the global level when sea levels rise and local agricultural conditions deteriorate (IPCC, 2014c). Other (non-GHG) emissions have impacts at the local level; here, too, the pressure is increasing in many developing and emerging countries. In terms of human health, hygiene and indoor air pollution are presently the major environmental causes of negative impacts.

This chapter shows how global growth in population and affluence has, over the long term, led to increased resource use and environmental impacts. Its focus is on the main impacts of the growing use of materials, land, water, and energy (although, as noted in Part I - Section 1.3, the treatment here is necessarily illustrative and selective, rather than comprehensive). This provides insight into the magnitude of the challenge of supplying a growing world economy with sufficient resources while remaining within the "safe operating space" of human activity, in order to avoid potentially very large negative impacts on human well-being. In the subsequent Part II - Chapter 2, trends in resource efficiency and decoupling will be explored, to investigate the potential for changes in the technology variable (T) in the IPAT identity to mitigate the effects of population (P) and affluence (A) on environmental impacts (I).

1.1. Use of materials

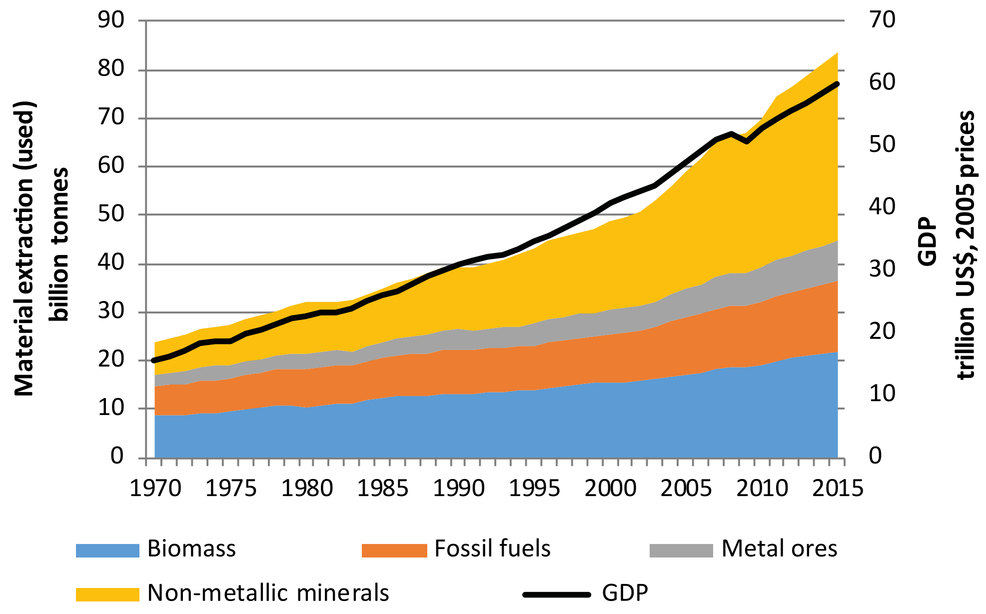
Material flow accounting (MFA) is an environmental accounting procedure that accounts for the material inputs and outputs of a system, and can be applied at various scales of social systems. This report mainly focuses on the level of national economies, or economy-wide MFA (EW-MFA). Recently, a global-level database has become available with national level EW-MFA time-series information for the period 1970–2010 (UN Environment, 2016a). Within EW-MFA, the material inputs and outputs of a national economy are measured in terms of the per capita throughput of primary materials – biomass, fossil fuels, metal ores and non-metallic minerals – that are required by the overall activities of the economy. These activities include the construction of physical infrastructure (for example, buildings, bridges, roads), energy-consuming activities such as transport and power generation, and the provision of edible biomass for animal livestock and human populations. This gives the economy a physical perspective, whereby natural resources are seen as factors of production and integral inputs into the production and consumption process. Materials are sourced from domestic extraction and imported materials (Fischer-Kowalski et al., 2011).

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

As already noted, resource use increased throughout the 20th Century. UN Environment (2011b) estimates that the amount of materials extracted and used globally – including ores, minerals, fossil fuels and biomass – increased eightfold between 1900 and 2005. This was twice the rate of population growth, but somewhat less than the rate of GDP growth, which has been estimated to have increased at least 19-fold, at constant prices, over the 20th Century (De Long, 1998). These statistics therefore present long-run evidence of "relative decoupling" of material extraction from GDP. However, such relative resource decoupling does not entail an absolute reduction in resources used. As shown in Figure 13, which shows trends in material extraction and GDP from 1970 to 2015, material extraction has continued to increase heavily. Indeed, according to these more recent data, since 2000 material extraction appears to have grown at a faster rate than GDP – suggesting the possibility of "recoupling" if this trend persists.

Underlying the global rates of material extraction illustrated in Figure 13 are different rates of material use and extraction in different countries and world regions. These rates can be analysed through different metrics, which account in different ways for the balance between domestically extracted material, imported material and material that an economy actually uses. The domestic material consumption (DMC) measure includes any materials extracted domestically, plus any imported materials, minus any exported materials. As DMC therefore represents the size of the material basis of the economy, it provides important information for comparing the material intensity of different economies. Organizations including the EC, Eurostat and the OECD have adopted DMC-based indicators for monitoring progress in sustainability and resource efficiency (Wiedmann et al., 2015). Growth in DMC may be due to population growth or to rising material use per capita. The DMC per capita indicator shows changes in material

Figure 13: Global material extraction in billion tons, and global GDP in trillion US dollars 2005 prices, 1970-2015



Source: Material extraction data from UNEP (2016a), GDP data from UNSD (2015).

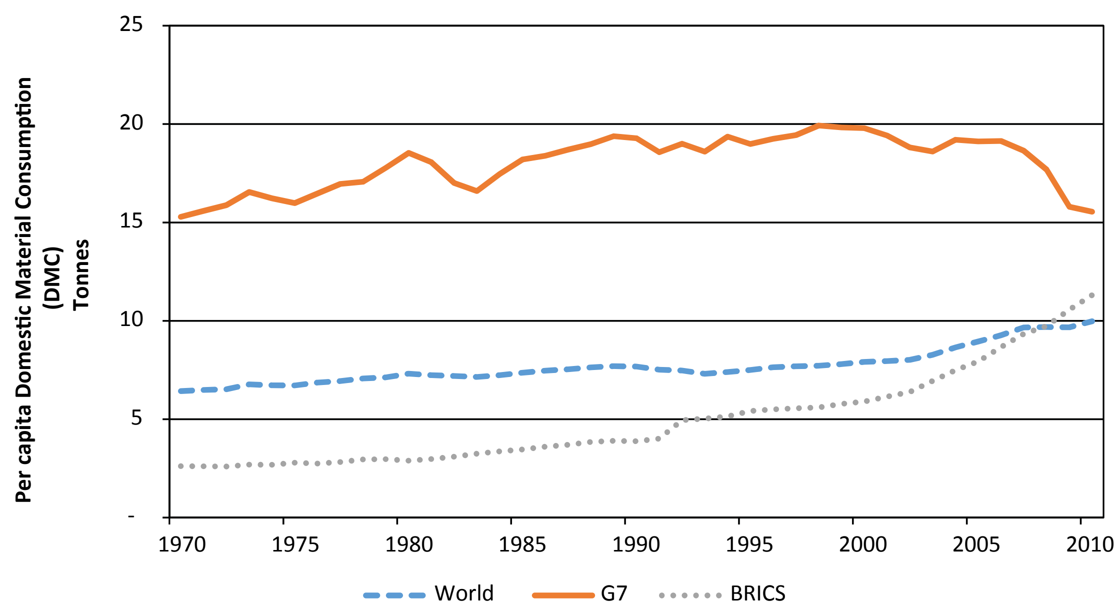
use independent of population and thus gives an indication of the material demand of a given structure of the economy.

Figure 14 shows the DMC per capita of the G7 countries, the BRICS[5] group of countries, and the world as a whole, from 1970 to 2010. In 1970, the DMC per capita of G7 economies was six times as high as the DMC per capita of the BRICS economies. However, by 2010 it was only 50 percent higher; this strong convergence of course also drives up the world average. This convergence was not only due to strong growth among the BRICS countries, but also to a relative stagnation, and even decline, among the G7 countries.

DMC in the G7 grew until 1995, stagnated for a decade, then declined sharply during the global financial crisis of 2008–09, when it fell back to the 1980s' level of per capita material consumption. The resulting compound annual average growth rate was at 0.04 percent over the full four-decade period. In comparison, DMC in the BRICS economies rose significantly over the same period, with a strong acceleration in growth since around the year 2000. The compound annual growth rate was 3.7 percent per annum. The average global DMC grew by an annual average of 1.1 percent between 1970 and 2010, from 6.4 tonnes per capita to 10 tonnes per capita, reflecting the growing demand for material in the global economy.

For G7 and BRICS countries' economies, as the rise of DMC could not be achieved through rising domestic extraction of natural resources alone, it was increasingly dependent on international trade. Such dependency, which has been increasing globally during recent decades, is highest for fossil fuels and metals. The structure of international trade has also been changing since the 1970s and 1980s, when the dominant pattern consisted of developing countries

Figure 14: Per capita domestic material consumption (DMC) in the G7, the BRICS and the global economy, 1970–2010, in tonnes

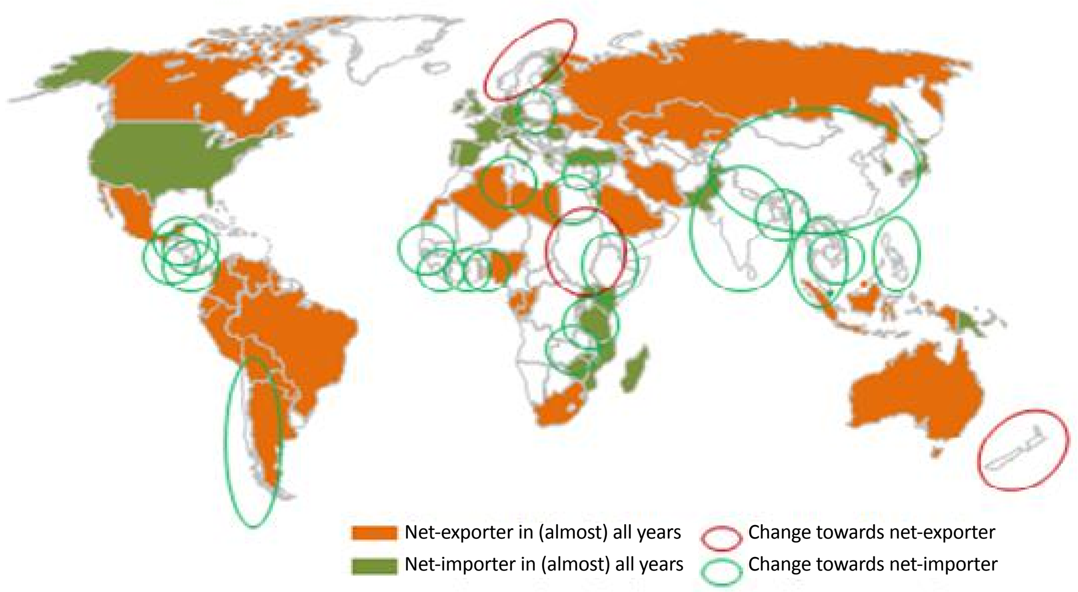


5 Brazil, Russia, India, China, South Africa.

delivering raw materials to high-income countries to be incorporated into industrial products, which they traded with other high-income countries. Today, a number of high-income countries (such as Australia or Canada) now play a major role in the provision of raw materials, and many more countries worldwide have become net importers of primary materials (Figure 15).

Figure 16 shows the DMC per capita of each of the G7 countries alongside the world average. G7 countries show a wide spread of per capita DMC, from around 10 tonnes per capita in Japan and the United Kingdom, to around 20 tonnes per capita in the United States and Canada (see Figure 16). These differences reflect the different material consumption levels of the population, but are also influenced by the differing extents to which raw materials are extracted for production domestically, as opposed to importing high-value but low material-mass products from other manufacturing countries. Within individual countries, DMC per capita has remained fairly

Figure 15: Persistence and changes in net-importing and net-exporting countries, 1962–2010



Source: Dittrich et al. (2012); UNEP (2015d).

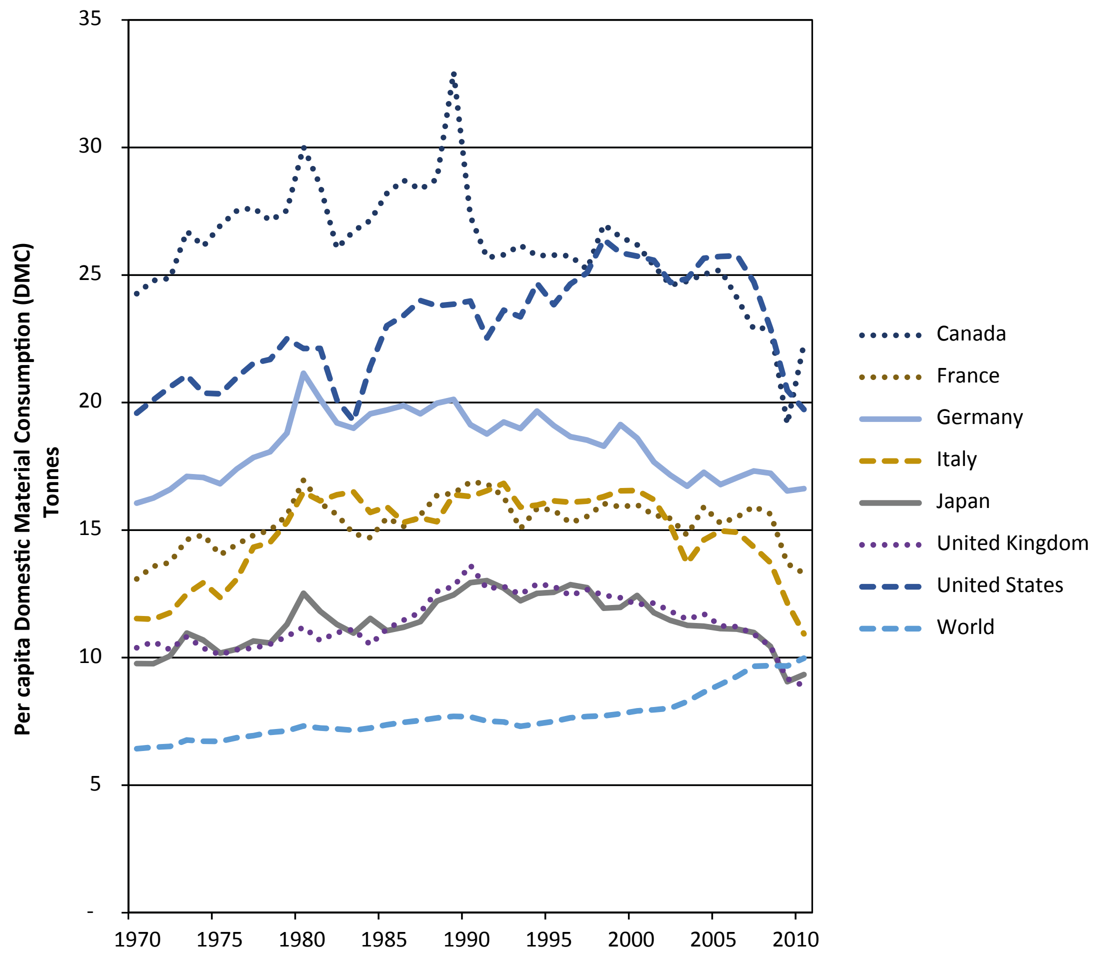
Part II: Resource efficiency: trends, economics and governance

stable over the last four decades, changing at yearly average rates of between 0.02 percent and 0.39 percent.

The BRICS group of emerging economies presents a very different picture (see Figure 17). In China, Brazil and to a lesser extent India, DMC per capita has grown substantially over the last four decades. China saw the fastest growth at 5.3 percent per annum, followed by Brazil at 2.4 percent and India at 1.7 percent. DMC per capita has declined in South Africa since the 1970s, and declined sharply in Russia following the dissolution of the former Soviet Union, but subsequently rebounded. In 2010, Russia, Brazil and South Africa had very similar levels of DMC per capita, while the highest level occurred in China at around 17 tonnes. The only BRICS country that experienced a significant sustained decline in DMC per capita was South Africa. This was a result of rapid population growth, which increased its population by almost 130 percent. Total DMC for South Africa was in fact around 75 percent higher in 2010 compared with 1970.

Another important indicator is the material footprint (MF) of final demand, which offers a consumption-oriented perspective on the material

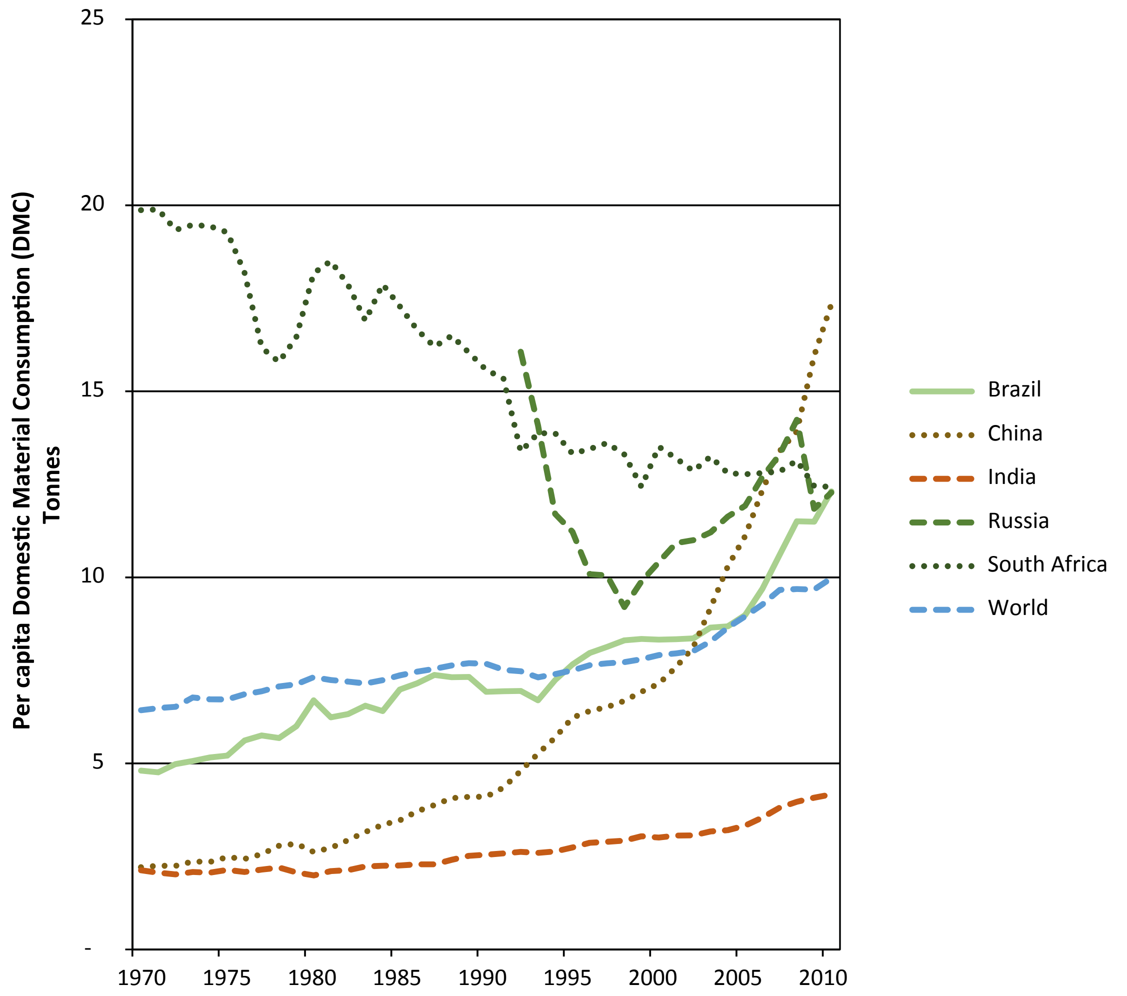
Figure 16: Per capita domestic material consumption (DMC) in G7 economies and the global economy, 1970– 2010, in tonnes



Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

requirements of nations. This indicator attributes global material extraction across the whole supply chain to the final demand in each country. The MF indicator is explained in detail in Wiedmann et al. (2015), who observe that "wealthier countries' imports of finished and semi-finished products are linked to a larger amount of raw materials compared with the physical quantity traded". Meanwhile, DMC attributes extracted raw materials to the extracting country's account, with importing countries attributed with the traded product. Wiedmann et al. (2015) note that "growing specialization, with some countries increasingly supplying primary resources for industrial development in other countries, means the burden of raw material extraction is shifting. The DMC shifts with it, as reflected in increasing DMC values for exporting countries and decreasing values for importing, mostly developed countries. The MF indicator, on the other hand, reallocates the burden back to the ultimate point of consumption, and is therefore less affected by specialization trends". Thus MF provides a useful complementary metric to DMC, as it relates all material extraction to the ultimate source of the consumption that is driving it. Due to MF's strong relation to consumption, it can be expected to increase with rising GDP per capita.

Figure 17: Per capita domestic material consumption (DMC) in BRICS economies and the global economy, 1970–2010, in tonnes



Indeed, Wiedmann et al. find a strong correlation, and that "as wealth grows, countries tend to reduce their domestic portion of materials extraction through international trade, whereas the overall mass of material consumption generally increases. With every 10% increase in gross domestic product, the average national MF increases by 6%". Thus material footprint per capita is strongly correlated to GDP per capita, and can be seen as a proxy for the material standard of living. As such, based on the previous trends analysed by Wiedmann et al., increasing GDP per capita in developing and emerging economies would be expected to be accompanied by an increasing MF.

Figure 18 shows that in 2010, the G7 economies' MF was almost 2.5 times that of the BRICS economies. This gap was much narrower than in the preceding decades, as the G7 group experienced a substantial decline in material standards of living following the 2008–09 global financial crisis, while MF growth for the BRICS group continued largely uninterrupted. In fact, the BRICS countries' MF is now approaching the global average, representing rising consumption in these countries. China dominated MF growth in the BRICS group, masking the stagnation and/or declines in MF per capita that occurred in South Africa and Russia. Analyses of the various factors that precipitated the profound decrease in material flows in Russia immediately following the dissolution of the former USSR, and its subsequent strong rebound from the mid to late 1990s, have been presented in West et al. (2014) and Krausmann et al. (2016).

Figure 19 shows some marked differences in the MF trajectories of G7 group countries. Interestingly, five of the G7 (Japan and the four European members) converged around an MF per capita of around 20 tonnes in 2010. This raises the question as to whether the closer EU integration over this period might explain this convergence for the European members. The two G7 nations that did not converge with the others

Figure 18: Per capita material footprint (MF) of domestic final demand in the G7, the BRICS and the global economy, 1990–2010, in tonnes

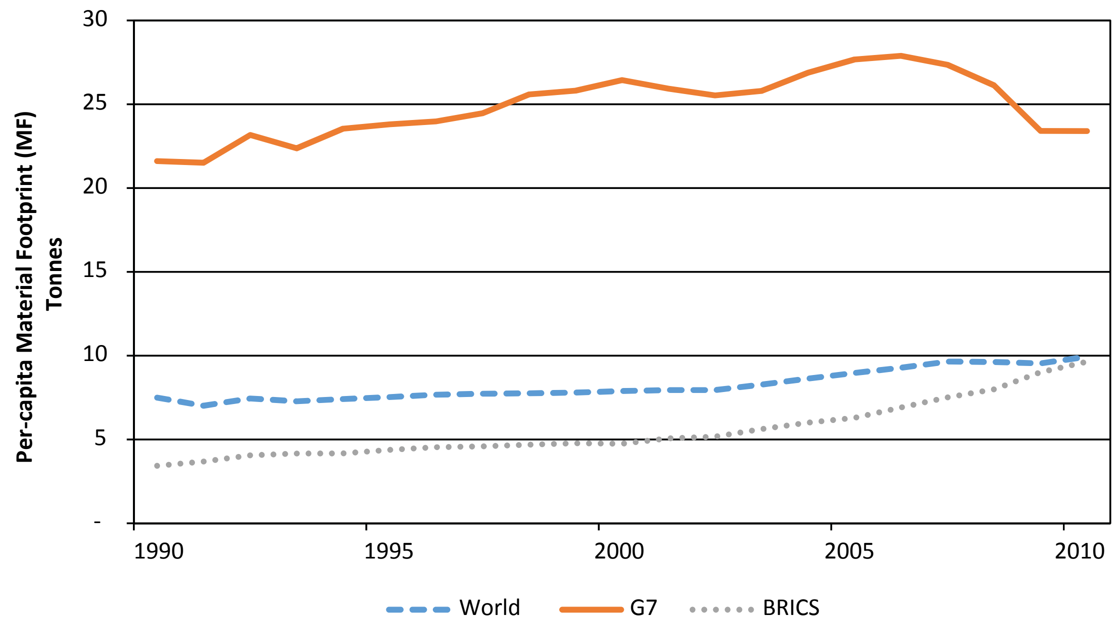
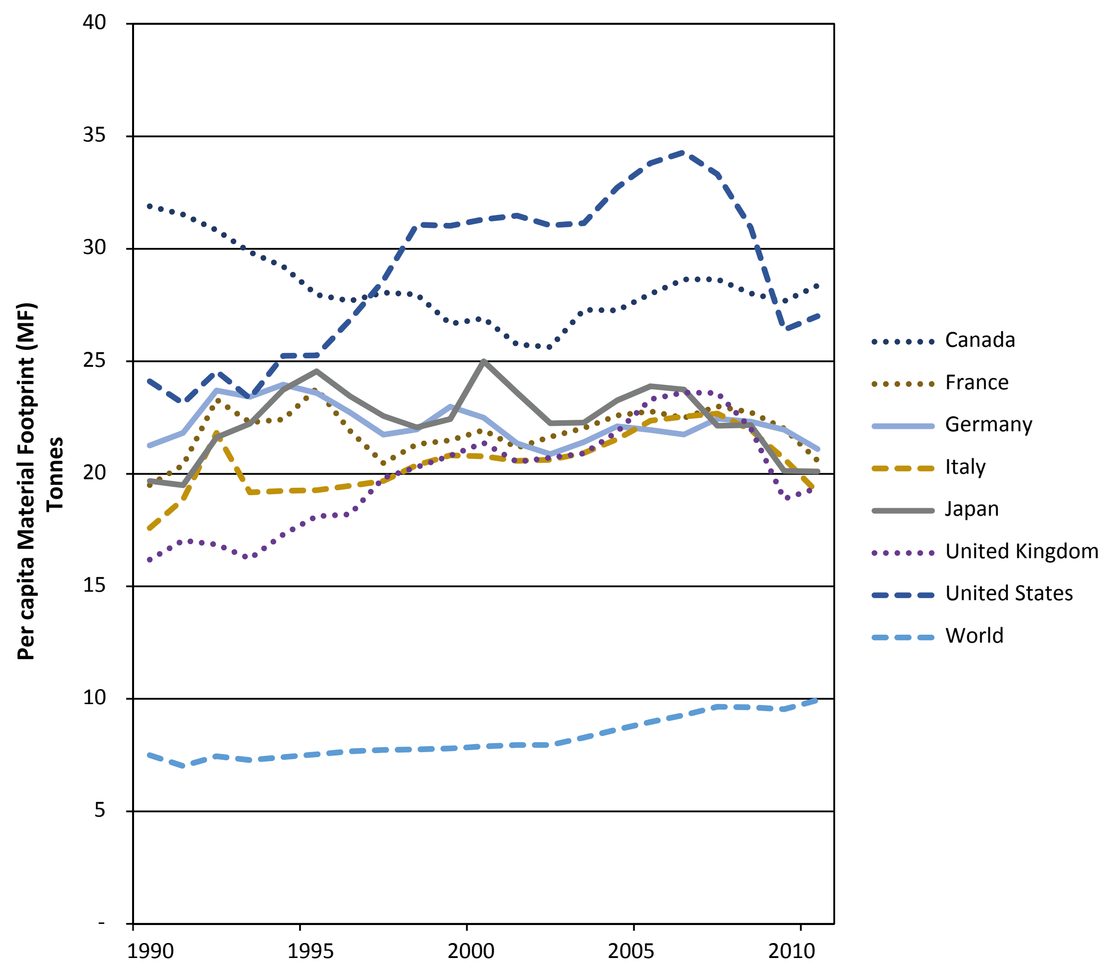


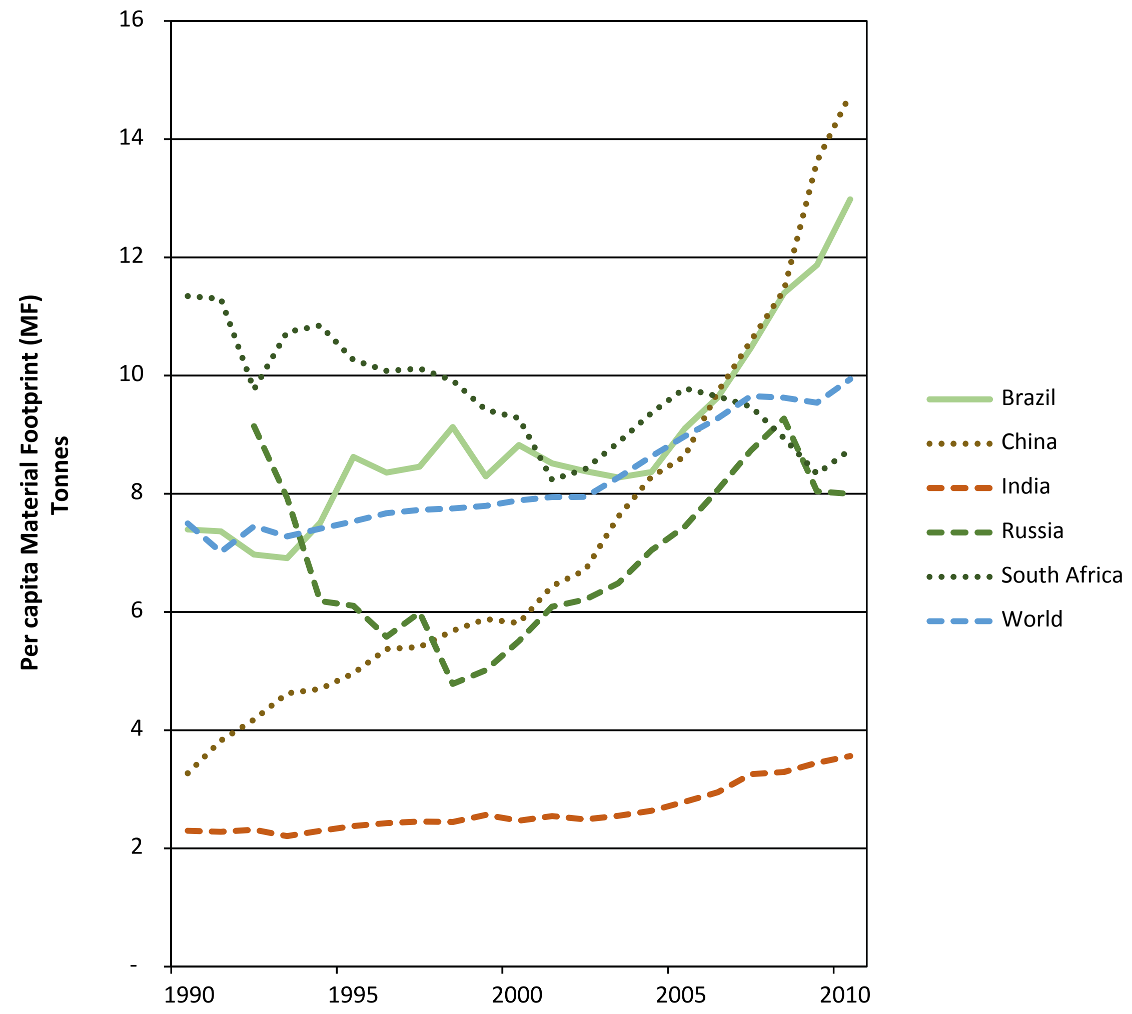
Figure 19: Per capita material footprint (MF) of domestic final demand in G7 economies and the global economy, 1990–2010, in tonnes



in this way have very different trajectories to each other. The US showed a more or less continuous increase up until the year immediately preceding the global financial crisis (GFC), at which point there is a rapid and accelerating contraction through to 2009. Canada, on the other hand, shows a prolonged period of decreasing MF for more than a decade, then a slow increase from the early 2000s, with only a shallow and short-lived contraction marking the GFC. Given the strong economic ties between Canada and the US, this is perhaps counter-intuitive. By contrast, the modest impact of the GFC on Canada's MF is much closer to that of the aggregated global curve than it is to the other members of G7. This may reflect the fact that extractive industries dominate Canada's economy more than the other G7 countries.

Figure 20 shows an even greater mix of trajectories in MF per capita for the BRICS group. Indeed, the lack of any coherent pattern here suggests that the original rationale for creating this grouping of nations may not have

Figure 20: Per capita material footprint (MF) of domestic final demand in BRICS economies and the global economy, 1990–2010, in tonnes



much relevance in understanding material flows and material footprints.[6] Although Figure 18 showed the clear trend of the BRICS group to average strong MF growth since the early 2000s, this largely just reflects the growth of China — its economic size tending to dominate any grouping to which it belongs. China's MF per capita grew at an average of 7.8 percent per year between 1990 and 2010, representing a considerable growth in affluence. The massive decrease, followed by a rebound, seen for Russia reflects the economic dislocation following the dissolution of the USSR, and subsequent recovery. The sustained decline seen for South Africa (a total reduction of 23 percent) was again largely the result of

6 The BRICS grouping (originally just BRIC) has developed a real organizational infrastructure; official BRICS summit meetings have been held between the relevant governments since 2009, and agreements to found a development bank and reserve currency pool were signed in 2014. The original grouping, however, appears to have been coined at Goldman Sachs in 2001, as a term to lump together a group of "emerging-market economies", largely for investment marketing purposes.

its relatively rapid population growth, as total MF actually increased moderately (8 percent) between 1990 and 2010. Brazil's growth in MF per capita (averaging 2.9 percent per year over the full period) was dominated by a major acceleration from 2003 onwards, where growth averaged 6.7 percent per year. This reflected the boost to Brazil's economy from a massive increased demand for its primary commodities, driven by China's growth. This boost came via both increased export volumes and increased unit prices for major commodities such as iron ore and oil.

1.2. Land use and land-use change

Very large areas of land are now cultivated to meet human needs and wants, including the production of biomass. According to FAO statistics, currently cropland covers 1,580 Mha or close to 11 percent of the world's land area, with agricultural land in total (including permanent pastures) covering 4,930 Mha or 33 percent of the world's land area. Total agricultural land increased by about 11 percent between 1961 and 2013 (FAO, 2016a). Globally, in 2005 humans consumed around 25 percent of the total biomass produced on Earth's land surface in that year (Haberl et al., 2014, Krausmann et al., 2013). Recently, increases in agricultural land in regions such as South-East Asia and South America have offset decreases in regions such as Europe and North America (FAO, 2016a). Dalgaard et al. (2008) connect reductions in cropland in Europe with increased imports of soybean for cattle feed from Latin America, replacing the domestic growing of fodder crops (Dalgaard et al. (2008), in UN Environment (2014a), p. 25). The location of any expansion of agricultural land is significant in terms of what type of land use it replaces, with the loss of primary forest — and its high levels of biodiversity — a particular concern in regions such as South America and South-East Asia (UN Environment, 2014a).

Agricultural land per person is unevenly distributed. Figure 21 shows trends in arable land plus permanent cropland per person, in different world regions. In all regions, the available land area per person has been declining due to rising populations. Nevertheless, Oceania still has particularly high arable and cropland availability per person, due mainly to large areas of agricultural land and low population densities in Australia and New Zealand. Although Europe and the Americas have considerably lower levels of arable and cropland per person than Oceania, in 2014 they had around twice the per capita levels of Africa and Asia. FAO (2011c) found that the availability of cultivated land in the developed world is, on average, around twice that of the developing world.

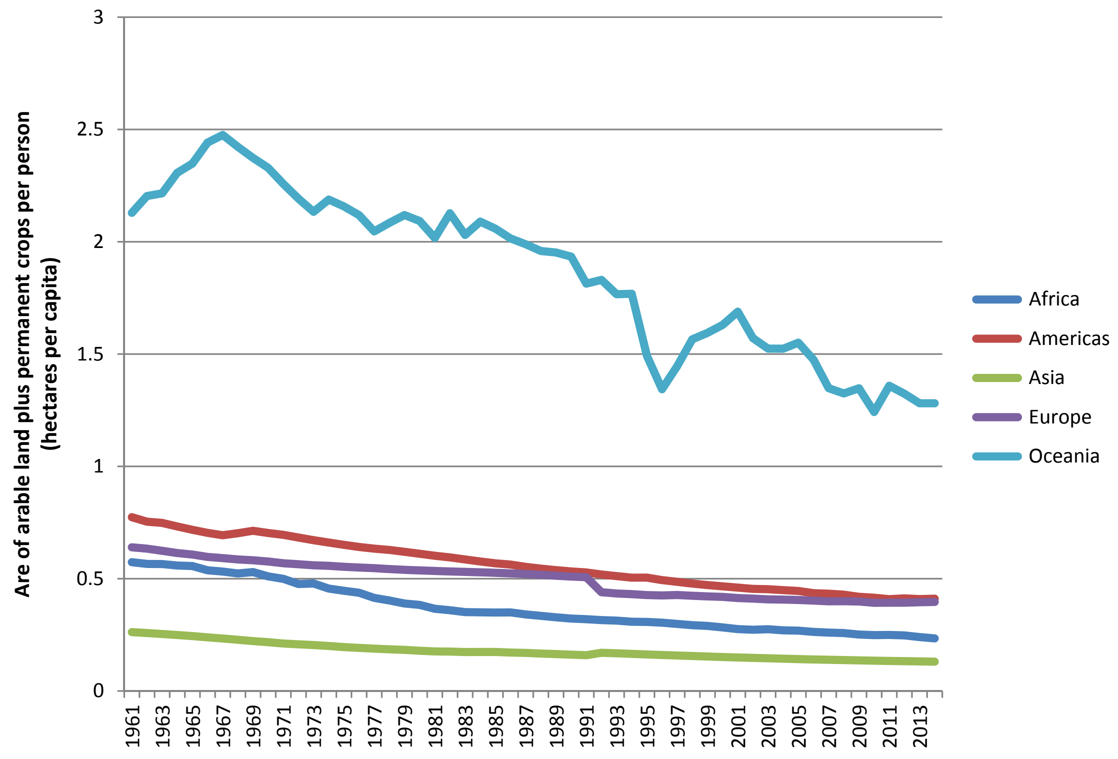
FAO (2011c) also suggests that, due to demographic pressures, the availability of cultivated land in developing countries could be halved by 2050. Projections for possible changes in available cultivated land per person in different world regions are shown in Figure 22.

The growing pressures on agricultural land use due to population increases can, to some extent, be compensated for by increasing land productivity, which has risen steadily in recent decades. This is largely driven by steady increases in agricultural inputs enabling a marked increase in agricultural production, while keeping additional land requirements at a modest level. Nevertheless, the growing use of biotic resources, in particular from agriculture, is contributing to rising pressures through land-use changes. Globally, the conversion of land to cropland has been responsible for the largest emissions of carbon from land-use change. In addition, cropland expansion into grasslands, savannahs and forests has a significant impact on biodiversity loss. The agricultural sector is not only by far the largest land user, but it also contributes significantly to resource depletion (of nutrients, especially phosphorus) and pollution (UN Environment, 2010).These effects are discussed further in Part II - Chapter 2.

Land use is expected to increase over the coming decades, due to the need for increased food production, and especially if biofuels come to

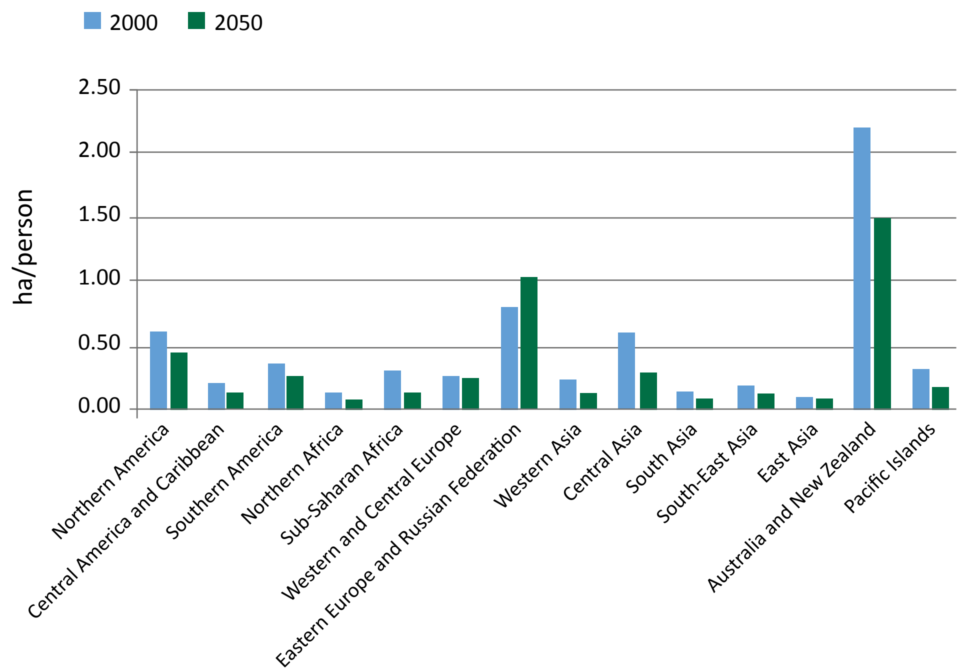
Part II: Resource efficiency: trends, economics and governance

Figure 21: Area of arable land plus permanent crops per person (hectares per capita), 1961–2013



Source: FAOSTAT (FAO, 2017).

Figure 22: Cultivated land per capita, 2000 and 2050

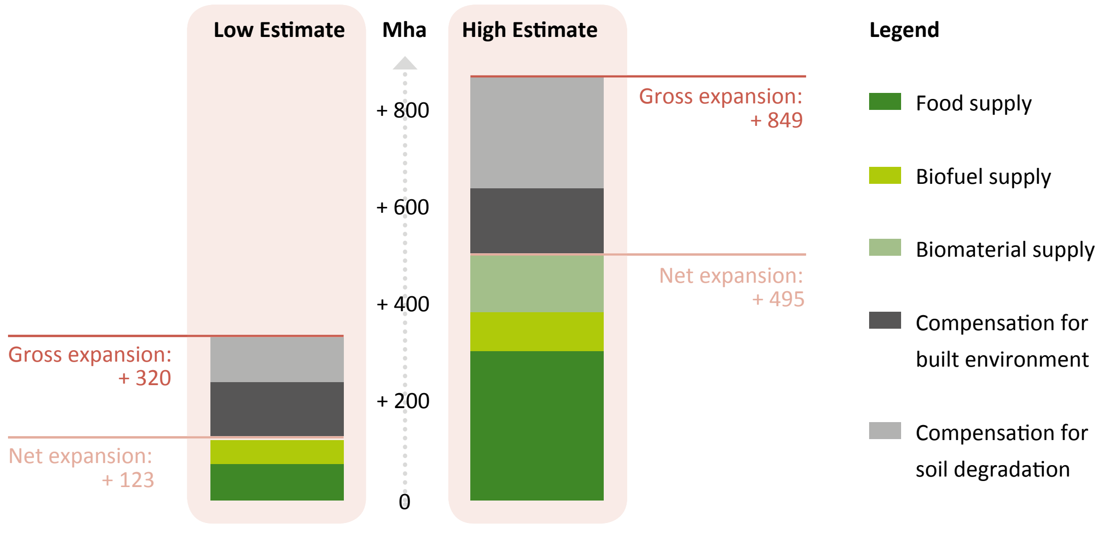


Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

have a significant share in the energy system. The demand for food supply is expected to be driven by population increases, rising incomes, and the need to combat malnutrition (Msangi and Rosegrant, 2009, UN Environment, 2014a). At present, access to food is unevenly distributed, with about 795 million people, or 11 percent of the world's population, undernourished in 2015. More than half of these undernourished people live in Asia, while sub-Saharan Africa has the highest prevalence, at 23 percent. The number of undernourished people has nonetheless decreased from around 1 billion in 1990, which at that time was almost 19 percent of the global population. In the same period (1990–2015), global meat consumption increased by 90 percent (FAO, 2015c). Food derived from rearing animals requires nearly five times as much land for a given level of nutrition as plant-based food (UN Environment, 2009b).

The FAO (2011c) projects that by 2050, global annual cereal demand will increase from about 2.1 billion tonnes currently, to about 3 billion tonnes. This will be accompanied by an additional annual demand of 200 million tonnes of livestock products (FAO, 2011c). Owing to the expected continued future growth in food demand, the OECD projects that global agricultural land (cropland and permanent pastures) will increase by a further 10 percent by 2030, and by 14 percent by 2050 (OECD, 2008a). In another UN Environment estimate, business-as-usual from 2005 to 2050 would lead to a net expansion of 123–495 Mha (an increase of 8 to 32 percent) and gross expansion of 320–849 Mha (an increase of 21 to 55 percent) of global cropland (UN Environment, 2014a). *Net expansion of cropland* results from rising demand for food and non-food biomass which cannot be compensated by higher yields. *Gross expansion* also includes the shift of cropland to other areas due to losses associated with severe degradation — in particular soil erosion — and built-up land. Without a more efficient use of food and non-food biomass in industry, retail businesses and households, the loss of biodiversity and additional greenhouse gas emissions through land-use change will continue to be enormous.

Figure 23: Trend of global cropland expansion from 2005 to 2050 for satisfying food demand and compensation of soil loss



Source: UNEP (2015c) p. 4.

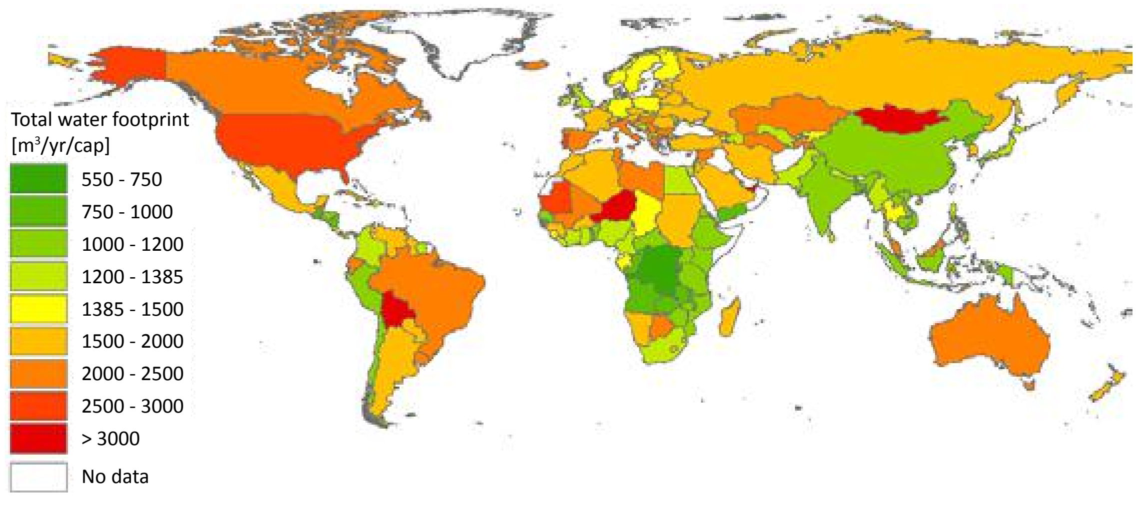
1.3. Water use

Access to clean water is another basic human need. Annual human water consumption grew from 600 billion cubic metres in 1900 to 4,500 billion cubic metres in 2010. At twice the rate of population growth (UN Environment, 2012d), such growth reflects increasingly water-intensive lifestyles, as well as industrial and agricultural intensification. At present, agriculture accounts for 71 percent of global water withdrawals, with the remainder being divided fairly evenly between industrial and domestic demand (Addams et al., 2009, FAO, 2011c). The importance of water to agricultural intensification is evidenced by the doubling of cropland equipped for irrigation between 1961 and 2013, as illustrated in Figure 34 in the following chapter. Energy production is also a significant consumer of water, with the sector currently accounting for around 15 percent of the world's total freshwater withdrawals (WWAP, 2015).

The total water use of an individual, a nation or an economic sector – accounting for direct as well as indirect consumption – can be assessed through a water footprint analysis. In their comparison of different nations, Hoekstra and Chapagain (2007) find the USA to present the highest average per capita water footprint, at 2,480m^3/capita/year – twice the global average of 1,240m^3/capita/year. High water footprints are also found in southern European countries such as Greece, Italy and Spain, as well as in Malaysia and Thailand. China has a relatively low water footprint of around 700m^3/capita/year, and water footprints in a number of other countries including Peru, Kenya, Zambia and Namibia are below 800m^3/capita/year. Figure 24 depicts average national per capita water footprints throughout the world.

As well as the water footprint, another key issue is the availability of renewable resources; the same water footprint may be more or less sustainable depending on the regional availability of renewable fresh water. Though the total amount of water in the global water cycle is unchanging, water resources in particular areas can become contaminated, stressed or critically depleted. Methods for defining levels of water stress include a water stress index,

Figure 24: Average national per capita water footprint (m^3/capita/year)



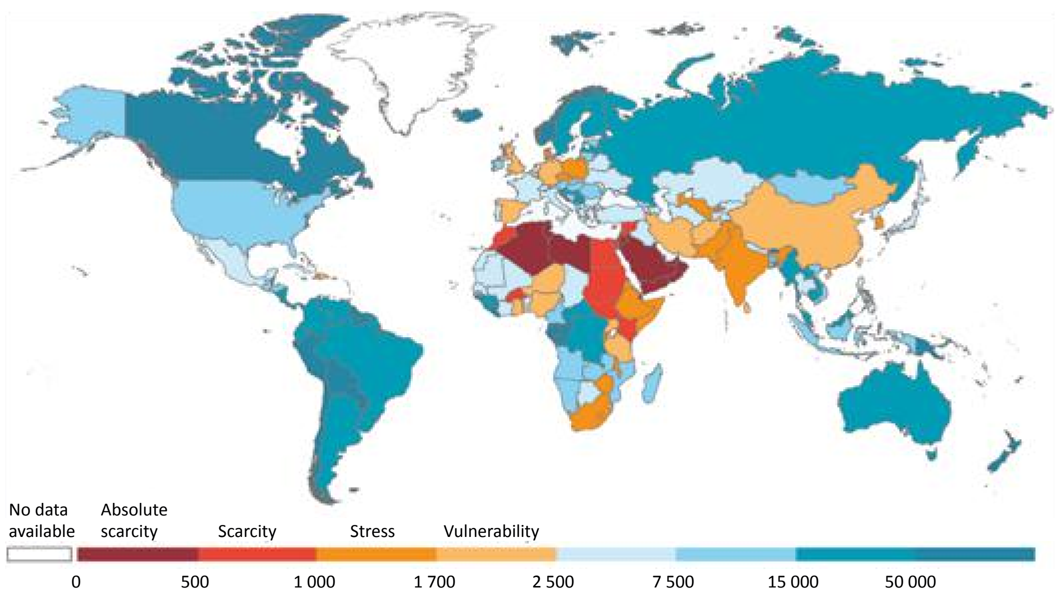
Source: Hoekstra and Chapagain (2007).

Note on Figure: Green signifies that the nation's water footprint is equal to or smaller than the global average. Countries shown in red have a water footprint greater than the global average (Hoekstra and Chapagain, 2007).

which measures the amount of renewable fresh water available per person per year. In one commonly used water stress index, a population with less than 1,700 m^3 of renewable fresh water available per capita per year is considered to be in a condition of water stress; less than 1,000 m^3 per capita per year is a condition of water scarcity, while absolute water scarcity describes an availability of less than 500 m^3 per capita per year (Brown and Matlock, 2011, OECD, 2013b). These thresholds underpin the categorization of countries in Figure 25, which shows that the risk of water stress is unevenly distributed globally.

Other methods of defining water stress bring together assessments of the rate of extraction, or water footprint, with assessments of available renewable resources, and consider them in relation to each other. In such measures of water stress, the rate of water consumption is expressed as a proportion of the rate at which the region's internal freshwater resources can be renewed. According to the FAO, a rate of water withdrawal above 20 percent of a region's available internal renewable water resources (IRWR) "represents substantial pressure on water resources – and more than 40 percent is 'critical'" (FAO, 2011c). East and South-East Asia have withdrawal rates close to 20 percent IRWR, while Western, Central and Southern Asia all have withdrawal rates greater than 50 percent. In North Africa, 201 percent implies that water is being extracted at a much higher rate than it can be replenished, resulting in unsustainable depletion of rivers and aquifers (FAO, 2011c). The OECD (2009) similarly considers water stress in terms of the ratio of total water use to renewable water supply. It defines the following thresholds: a ratio of extraction to renewable supply of less than 10 percent is considered "low stress"; 10–20 percent "moderate", 20–40 percent "medium" and above 40 percent "severe". It

Figure 25: Total renewable water resources per capita (2013)



Note: The figures indicate total renewable water resources per capita in m^3.
Source: WWAP, with data from the FAO AQUASTAT database. (http://www.fao.org/nr/water/aquastat/main/index.stm) (aggregate data for all countries except Andorra and Serbia, external data), and using UN-Water category thresholds.

Source: WWAP (2015), p. 12.

estimates that in 2005, 44 percent of the world's population was living in areas characterized by severe water stress (OECD, 2009).

It is projected that by 2030, with average economic growth and no efficiency gains, global water demand will rise from 4,500 billion cubic metres to 6,900 billion cubic metres. This is calculated to be 40 percent higher than currently accessible, reliable supplies (Addams et al., 2009, WWAP, 2015). However, this global average deficit masks greater regional variation, with Addams et al. suggesting that by 2030 "one-third of the population, concentrated in developing countries, will live in basins where this deficit is larger than 50 percent" (2009). There are also significant regional differences in the projected overall increased demand for water. For example, Addams et al. (2009) project demand in sub-Saharan Africa to increase by 283 percent from 2005 levels, driven largely by increased use in agriculture. In other regions, less extreme — but nonetheless in themselves considerable — increases in demand are projected. For example, North America's demand is projected to increase by 43 percent, as shown in Table 4.

Such increases in global demand will be hard to sustain. The OECD estimates that by 2030, the number of people falling into its "severe" water stress category will reach 3.9 billion, or around 47 percent of the world's population, mostly in non-OECD countries (OECD, 2009). This may affect food prices and could lead to conflict, while increasing climate change could further exacerbate such problems (WWAP, 2015). Water scarcity is therefore a serious concern in many parts of the world.

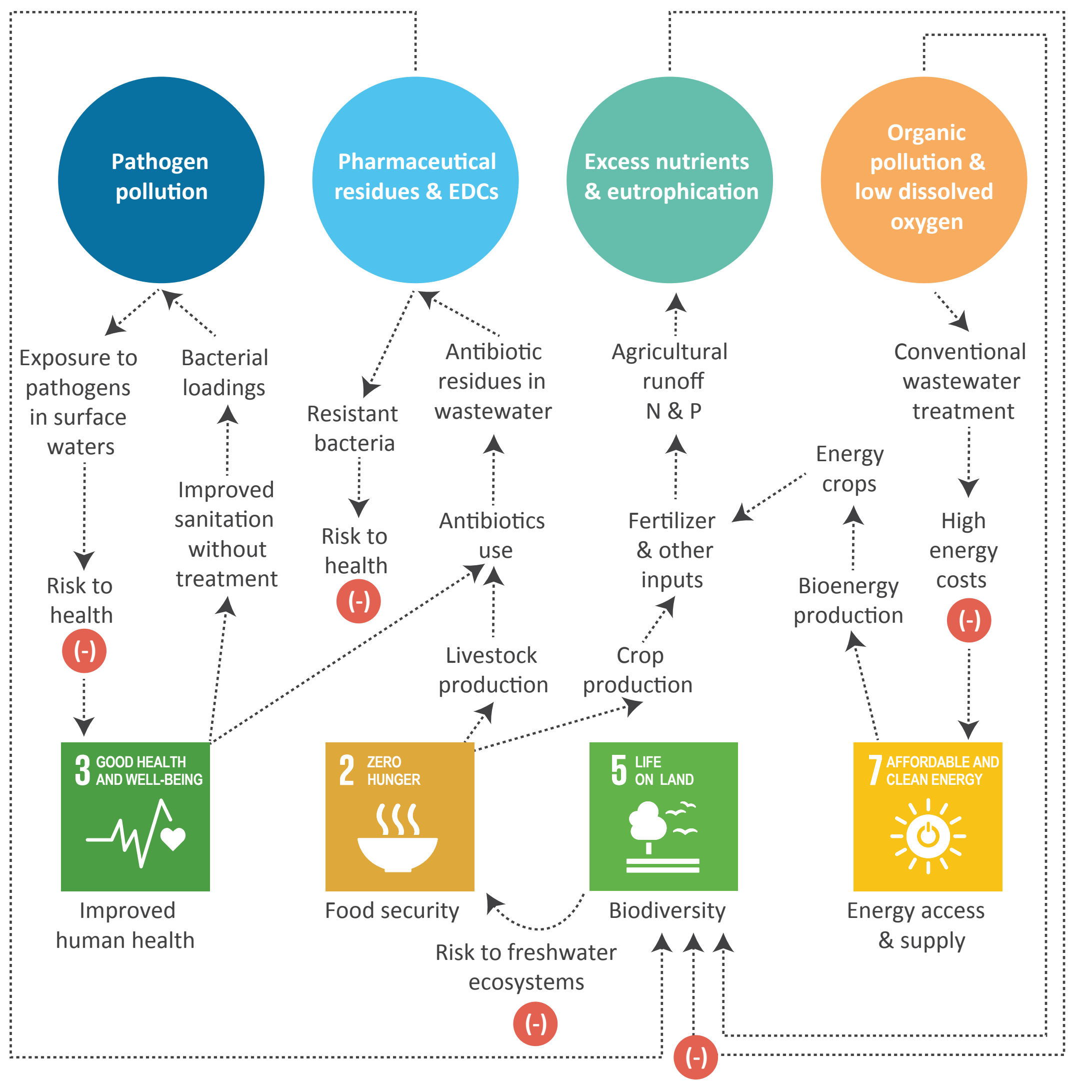
There are also worries over deteriorating water quality. As shown in Figure 26, water quality has strong linkages to several of the SDGs. Pressures include pathogen pollution (e.g. from sewer discharge), organic pollution (including from plant nutrients in agricultural run-off), and salinity pollution (including from irrigation, domestic wastewater and run-off from mines). Although water pollution is worsening in many parts of Latin America, Africa and Asia, the majority of rivers on these continents are in good condition — the major pollution sources are spatially concentrated, meaning that the impacts are unevenly distributed. This makes monitoring and evaluation crucial, although insufficient

Table 4: Increases in annual water demand, 2005–2030

Region	Projected Change from 2005
China	61 percent
India	58 percent
Rest of Asia	54 percent
Sub-Saharan Africa	283 percent
North America	43 percent
Europe	50 percent
South America	95 percent
Oceania	109 percent

Source: Addams et al. (2009).

Figure 26: Linkages of water quality with selected Sustainable Development Goals



Source: UN-Water (2016).

data are available in many parts of the world. Improving the collection, sharing and analysis of data on water quality is therefore an urgent priority (UN-Water, 2016).

Marine and aquatic ecosystems are also under pressure, with marine biomass threatened by unsustainable levels of exploitation. In 2013, 58 percent of fish stocks were fully fished, while 31 percent were estimated to be "fished at a biologically unsustainable level and therefore overfished" (FAO, 2016b). These levels of extraction seriously threaten some fish populations.

1.4. Energy use and greenhouse gas emissions

The production and use of energy place significant pressure on the environment. The main source of primary energy, fossil fuels (coal, oil and gas), and the associated greenhouse

gases, acidifying substances, nutrifying substances and air pollutants are an important source of environmental impacts. Since 1945, primary energy production at the global level has tripled, and since 1970 it has increased by a factor of two. Total primary energy supply (TPES) per capita also increased from 1974 to 2009. At the global level, this increase was slight: less than 10 percent over the 40 year period. The most marked increase can be observed in China (IEA, 2011), where TPES per capita grew by a factor of four to reach the average world level. China is now the country with the largest share in global GHG emissions. Figure 39 and Figure 40 in Part II - Chapter 2 compare TPES per capita, and per capita CO_2 emissions, for a range of countries and world regions.

Fossil fuels remain the world's primary energy source and the main component of GHGs.

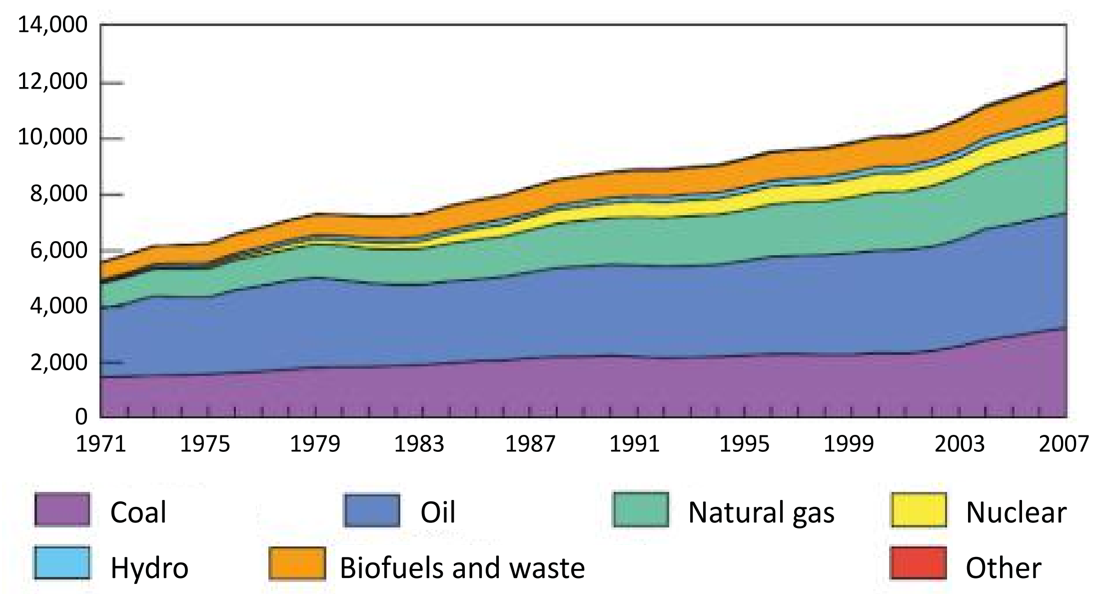
Figure 29 shows the breakdown of anthropogenic GHG emissions in 2010, by economic sector.

Direct emissions refer to emissions generated within the economic sector listed. Indirect CO_2 emissions refer to the emissions arising from the production of an intermediary fuel or energy vector — such as heat or electricity — which is then used in one of the sectors.

Figure 29 shows that the production of electricity and heat from fossil fuels accounts for around a quarter of total GHG emissions. However, from a demand perspective, when all intermediate energy vectors (such as electricity) are allocated to the sector of their final consumption, the majority of GHG emissions are generated by the major energy-using sectors, industry, buildings and transport, which together account for around 65 percent of GHG emissions.

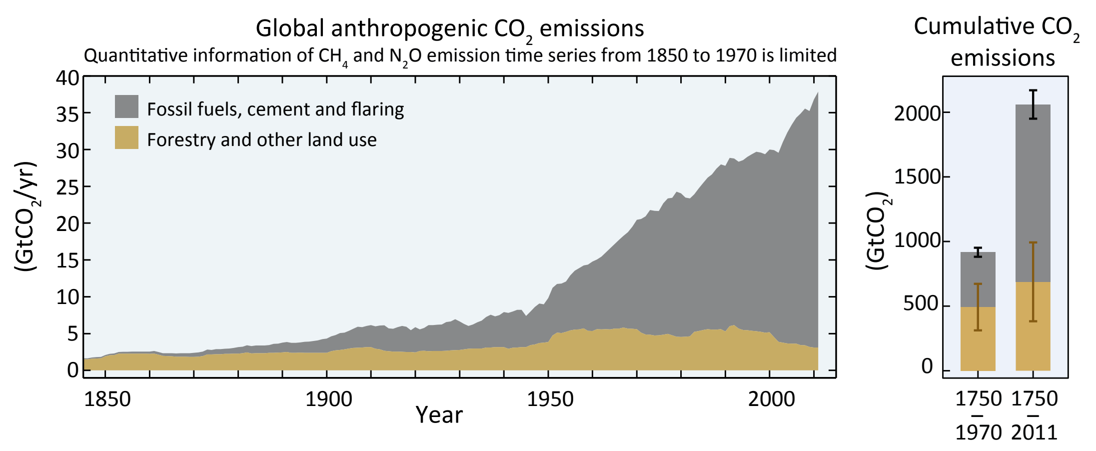
A further important issue relating to energy GHG emissions concerns whether responsibility is allocated on a production or consumption basis: should responsibility for emissions associated with the production of goods lie with the country

Figure 27: World total primary energy supply, 1971–2013



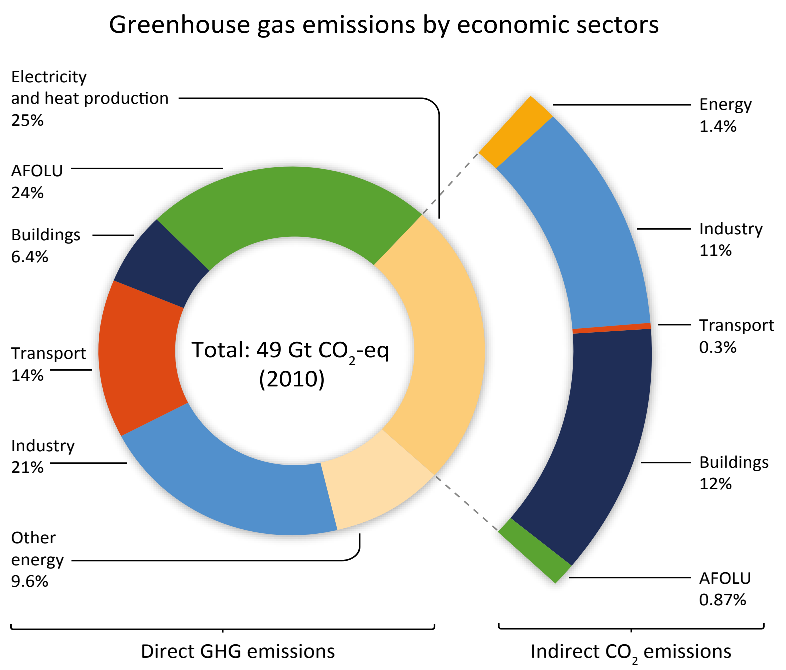
Source: IEA (2015).

Figure 28: Global annual and cumulative greenhouse gas emissions at various dates



Source: IPCC (2014c).

Figure 29: Total anthropogenic GHG emissions (Gt CO_2eq per year) by economic sector: energy, industry, transport, buildings, and agriculture, forestry and other land use (AFOLU)



Source: IPCC (2014d).

in which the goods are manufactured, or with the country to which the final product is exported? This is a particularly critical issue for international agreements on climate change in the context of increasing volumes of global trade. It is estimated that about a quarter of global CO_2 emissions are embodied in international trade, with a significant proportion of these embodied in trade from non-carbon-priced to carbon-priced economies (Sakai and Barrett, 2016). The emissions embodied in products imported by industrialized nations tend to be higher than the emissions embodied in the products they export – that is, industrialized nations are typically found to be net importers of CO_2 emissions (Peters and Hertwich, 2008).

1.5. The "resource nexus"

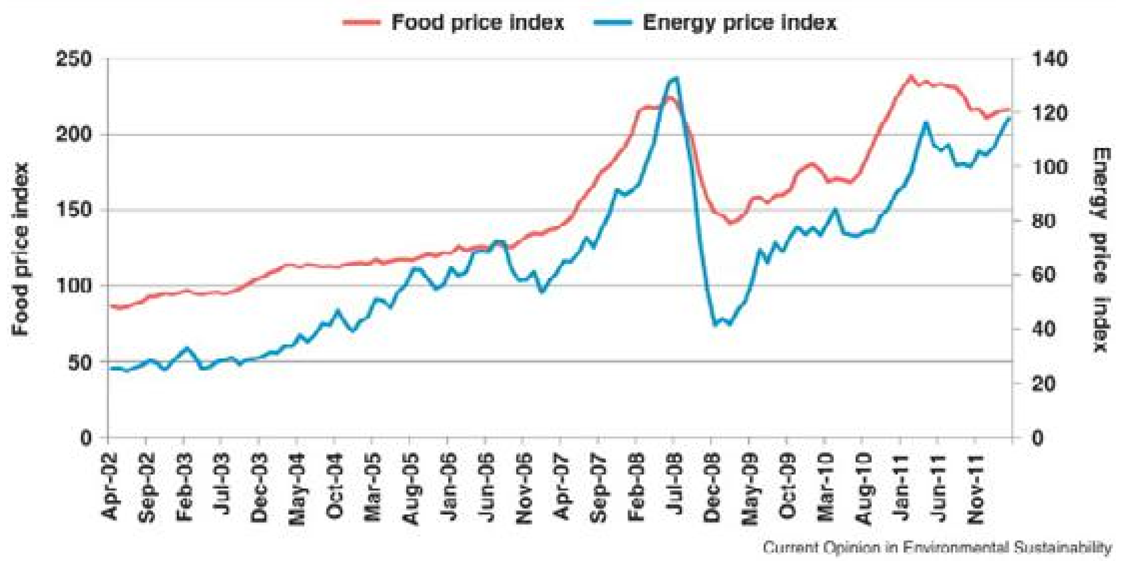
Although materials, land, water and energy have been discussed in turn in the preceding sections, the drivers and impacts of human uses of these various resources are clearly not isolated from each other. Rather, there are pervasive interactions between different types of resources, which are often reciprocal and dynamic in nature. The importance of these resource interactions, both as drivers of resource pressures and as opportunities for potential solutions, is increasingly widely understood, and is now often discussed within the concept of the "resource nexus".

This concept was brought to the fore in 2011, by a conference in Bonn, Germany, entitled "The Water, Energy and Food Security Nexus – Solutions for the Green Economy". The background document to the conference emphasized "the increasing interconnectedness across sectors and in space and time", and that a nexus approach could help increase overall resource efficiency in water, energy and food, "by addressing externalities across sectors" (Hoff, 2011). For example, "nexus thinking would address the energy intensity of desalination [...] or water demands in renewable energy production (e.g. biofuels and some hydropower schemes) or water demands of afforestation for carbon storage." Nexus thinking thus aims to avoid approaches that focus solely on individual resource categories, without considering their knock-on effects: "the nexus focus is on system efficiency, rather than on the productivity of isolated sectors" (Hoff, 2011). As well as understanding possible pressures and cross-sectoral externalities, the nexus approach also has the potential to identify measures that can create positive impacts across more than one sector — "additional opportunities can be realized if the nexus is addressed coherently across all scales through multi-level governance" (Hoff, 2011). A range of studies have used a nexus approach to explore interactions and synergies between water, energy and food (FAO, 2014c, Kurian, 2016), as well as with land (Ringler et al., 2013), minerals (Andrews-Speed et al., 2012), ecosystems (de Strasser et al., 2014, Rasul, 2012) and climate change (Waughray, 2011).

Given the interconnectedness of resources, nexus issues emerge quite naturally throughout this report. These include situations of increasing pressure, where two or more resources experience pressure due to the same or similar drivers, or examples where an action in relation to one resource unintentionally places pressure on another resource. However, the report also finds many examples of synergistic opportunities, where an action can have beneficial impacts for more than one resource.

For example, as the food system is highly interconnected with several resource flows, Part III - Chapter 4 emphasizes the importance of a "food systems" approach to account for these interactions. As one illustration, Figure 30 shows food and energy prices from April 2002 to March 2012 (Ringler et al., 2013). The figure suggests a strong correlation between food prices and energy prices, and indeed Ringler et al. (2013) report that the correlation coefficient between the two indices over this period was 0.94. Ringler et al. suggest the following possible reasons for the strong correlation: "(i) agriculture is becoming increasingly energy-intensive through increased use of fertilizers, machinery and groundwater pumping; (ii) biofuel development from maize

Figure 30: World food and energy price indices, April 2002 to March 2012



Source: Ringler et al. (2013).

in the United States under the US Energy Policy Act of 2005 has led to a direct competition for land, water, energy, capital and labor between food and energy production; and (iii) financial investments in agricultural commodities have increased" (Ringler et al., 2013). This summary of interactions between food and energy prices clearly highlights how numerous and multi-directional the influences between different resources and systems can be.

In Part II - Chapter 2, Figure 34 also illustrates the important interactions between water, food, energy, minerals and land use. It shows the increasing productivity of cropland in recent decades, which has allowed the overall expansion of cropland to take place at a slower rate than the rate of increase in food production from this land. This is of course beneficial in that it has enabled a smaller extent of land-use change than would have been the case without the productivity increase. However, as discussed in Part II - Chapter 2, this increased productivity has been achieved as a result of large increases in irrigation, causing increased water demand, with agriculture currently accounting for 71 percent of global water withdrawals (Addams et al., 2009, FAO, 2011c). Figure 34 also shows that increased cropland productivity has been accompanied by dramatically increased inputs of fertilizer, which causes increased demand for both minerals and energy.

The increasing use of land to produce food to feed growing populations may also have significant impacts on biodiversity. As discussed in Part II - Section 1.2, recent increases in agricultural land in regions such as South-East Asia and South America have offset decreases in regions such as Europe and North America (FAO, 2016a). The location of currently expanding agricultural areas is highly significant — the loss of primary forest, with high levels of biodiversity, is a particular concern in regions such as South America and South-East Asia (UN Environment, 2014a). As discussed in Part II - Section 2.2 , UN Environment (2014a) estimates that current trends — accounting for various pressures including increasing demand for biofuels and biomaterials, and loss of land to the built

environment and to soil degradation — could lead to an expansion of cropland by 2050 well in excess of a reasonable "safe operating space". This makes increasing resource efficiency in land use critically important, while at the same time avoiding the negative impacts associated with rising use of fertilizers, pesticides and other agricultural inputs. Land use also has significant climate change implications, as shown in Figure 29 from the IPCC (2014d): around 24 percent of global annual GHG emissions currently come from agriculture, forestry and other land use.

Water and energy is another important nexus, with the energy production sector currently accounting for around 15 percent of the world's total freshwater withdrawals (WWAP, 2015). Thermal power plants use significant amounts of water for cooling, and the subsequent discharge of higher temperature water into rivers, lakes and reservoirs creates thermal emission "hotspots", which have negative impacts on aquatic ecosystems (Raptis and Pfister, 2016). Hydropower plants can also have serious impacts on water supply and aquatic ecosystems, as discussed in Part III - Section 6.2. Furthermore, if biofuel production is scaled up as a source of low-carbon fuel, a further increased demand for water will emerge, as the water demand of biofuels per unit of energy delivered can be greater than that of thermal fossil fuel plants (Hoff, 2011). UN Environment (2009b) suggests that bio-based energy may be severely bound by constraints on land and by water use, although advanced or "second generation" biofuels, produced from lignocellulosic plant material, or potentially from aquatic biomass such as algae, might mitigate such conflicts (Langholtz et al., 2016, Martín and Grossmann, 2015, de Vries et al., 2014).

There is also an important nexus between energy and materials. One issue is that although renewable energy systems are generally less polluting than fossil-fuel-based systems, they tend to use more metals in construction per unit of energy delivered (UN Environment, 2015b), as discussed in Part III - Chapter 6. The energy requirement of metal production itself is also subject to change: lower-grade ores require more energy per kg of produced metal for refining. This impact will become more pronounced as metal demand rises. This may to some extent counteract the effectiveness of the transformation towards a renewable energy system (UN Environment, 2013b). Such nexus issues, which are crucial when assessing the criticality of different resources and the environmental impacts of resource use, are the subject of ongoing work in the International Resource Panel.

Life cycle analysis (LCA) will be critical to understanding many such resource interactions, and the full implications that choices made in relation to one resource could have on its interconnected resources. Results of LCA studies are reported and discussed throughout this report, including in relation to material efficiency strategies (Part III - Chapter 2), transport technologies and fuels (Part III - Chapter 5), and power generation technologies (Part III - Chapter 6).

Although a nexus perspective can identify potential challenges, conflicts and trade-offs emerging from the interaction of different resources, it can also help identify synergistic opportunities, or "win-win" actions, that have beneficial effects across more than one resource area. As noted by Hoff (2011), "additional opportunities can be realized if the nexus is addressed coherently across all scales through multi-level governance".

For example, in water-stressed areas that have resorted to energy-intensive water production measures such as desalination, water-saving measures would save both water and energy. Meanwhile, as discussed in Part II - Section 2.2 and Part III - Chapter 4, increased efficiency in food production and consumption can save land, water and energy, while more efficient irrigation methods can save water and increase land productivity (Part III - Section 7.1). Recycling of

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

nitrogen and phosphorus nutrients from waste streams back into agricultural inputs, as discussed in Part III - Section 7.2, both reduces pollution and increases land productivity. More efficient use of materials in manufacturing as well as in municipal waste management typically saves both energy and resources (Part II - Chapter 1 and Part III - Section 7.3).

Although the transition from fossil-fuel-based energy to renewables may entail some nexus challenges — due to increased demand for certain materials and, for biofuels and hydropower, potentially increased water demand – there are also important nexus benefits of such a transition. As discussed in detail in Part III - Chapter 6, renewable-electricity generation technologies, as well as reducing carbon emissions, also offer reduced impacts across a range of other indicators, including eutrophication, ecotoxicity and particulate matter emissions.

Cities constitute systems of major importance through which all of the major resources flow. As discussed in Part III - Chapters 3 and 5, well-designed cities — incorporating energy-efficient buildings, high-density, mixed-use settlements well-served by public transport, walking and cycling lanes, and green spaces — can have numerous complementary and mutually reinforcing benefits. For example, high-density, mixed-use settlements tend to have lower energy consumption per household. Their density also allows shared infrastructures for recycling and reuse of materials and water to be used more effectively, and can dramatically reduce private vehicle transport demand due to ease of access to destinations and good public transport links. The reduction in private vehicle transport demand in turn reduces both car ownership and the need for car parking spaces. This favours more green spaces and reduces the land area that is covered by impermeable surfaces, thereby improving groundwater recharging.

As well as identifying connections between systems and resource flows, nexus thinking also emphasizes the crucial links between environmental sustainability and human well-being. This is in line with the 2030 Agenda for Sustainable Development, with its 17 SDGs, which offers a comprehensive framework that brings together aspirations for human development and the protection of the natural systems on which this depends. Ringler et al. (2013), writing before the SDGs had been agreed, emphasized the importance of this agenda, and its critical connection with nexus thinking: "as resource uses are dependent on one another with respect to human well-being and environmental outcomes for present and future generations, a rigorous theoretical framework is required to co-balance the costs of trade-offs and identify the synergies across them in order to explicitly incorporate all goals… The SDGs, if designed correctly, appear to be an ideal vehicle for realizing this vision of co-benefits for humankind and nature" (Ringler et al., 2013). As discussed in Part IV - Chapter 1, the SDGs do indeed provide an important vehicle, and a major opportunity, for identifying crucial synergies and maximizing such "co-benefits for humankind and nature".

Nevertheless, adopting a nexus perspective can entail complexities for policymakers. For purely practical reasons, separate ministries typically take responsibility for each of the various resources and systems described in this report. This is understandable and largely beneficial, as it allows policymakers to achieve tractable and demonstrable progress on particular issues. However, policymakers should also attempt to balance a resource-specific or sectoral-focused approach with a more cross-sectoral, cross-resource and full-supply-chain perspective. This is both to avoid unintended consequences of policy actions, and to maintain awareness of the potential for win-win opportunities if sectors or resources are considered more holistically.

1.6. Conclusions

It is clear from the previous discussion that the physical economy has grown rapidly over the 20th Century, driven both by rising populations and rising affluence. As suggested by the IPAT identity,

these increases in population (P) and affluence (A) have resulted in increased environmental impacts (I), including from substantial increases in the extraction and use of materials, water and energy, and the appropriation of land for human uses. The associated pressure on resources and accumulation of environmental impacts are such that scientists are warning of breaching the "planetary boundaries" that delimit the "safe operating space" of human activities.

In developed countries, the growth in the direct use of materials, energy, land and water has slowed down to some extent. However, the picture becomes more complex when trade effects are taken into account. Growing volumes of trade increasingly enable developed countries to "offshore" both the material footprint and the emissions footprint of their consumption activities to emerging economies.

Presently, the largest growth in per capita domestic material consumption (DMC) is occurring in emerging economies such as China, Brazil and India. This is largely related to the growing infrastructure in these countries, supported by the rise in economic activity combined with the process of urbanization. The growth also reflects an economic structure with a higher proportion of heavy industry and manufacturing than in the economies of many industrialized countries, in which heavy industry has been reducing for some decades, and services increasing, in relative importance. In developing countries, the average level of affluence measured in per capita material footprint terms remains substantially lower than in developed economies. A considerable increase in resource use is still to be expected in these countries if they achieve their aspirations for economic development. In many developing countries, growing populations will further add to the increase in resource use.

The growth in agricultural land use in recent decades has been less rapid than, for example, the growth in the extraction of materials, due to substantial increases in agricultural productivity. However, here too challenges lie ahead. Current widespread levels of malnutrition and rising populations require expansion in terms of food production. However, the safe operating space for the expansion of agricultural land is strictly limited, due to potentially deleterious effects on forests and other ecosystems.

The availability of renewable fresh water varies greatly between locations, yet particular regions are already under severe water stress. Again, this will be exacerbated by rising populations and increasing agricultural production.

Energy use is also central to human development, and yet the majority of energy is supplied by fossil fuels, which have a number of negative impacts. There is an urgent need to reduce these impacts, without compromising the much needed development that increased energy access can bring.

The challenge of the 21st Century is therefore to meet the needs of a growing global population with a rising level of affluence, without increased resource consumption and environmental impacts taking human activities outside the "safe operating space" that protects human well-being. Central to this challenge will be resource efficiency, a key strategy for enabling a "double decoupling", of economic development from resource use, and of resource use from environmental impacts (as already discussed above).

2. TRENDS IN RESOURCE EFFICIENCY, DECOUPLING AND ECO-EFFICIENCY

One possible way of reducing the pressure of humanity's growing resource system, and of keeping humanity's environmental impacts within planetary boundaries, is through developments in resource efficiency. Referring back to the IPAT identity introduced in Part II - Chapter 1, this amounts to reducing environmental impact (I) – despite ongoing increases in population (P) and affluence (A), which are both expected to continue to grow at the global

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

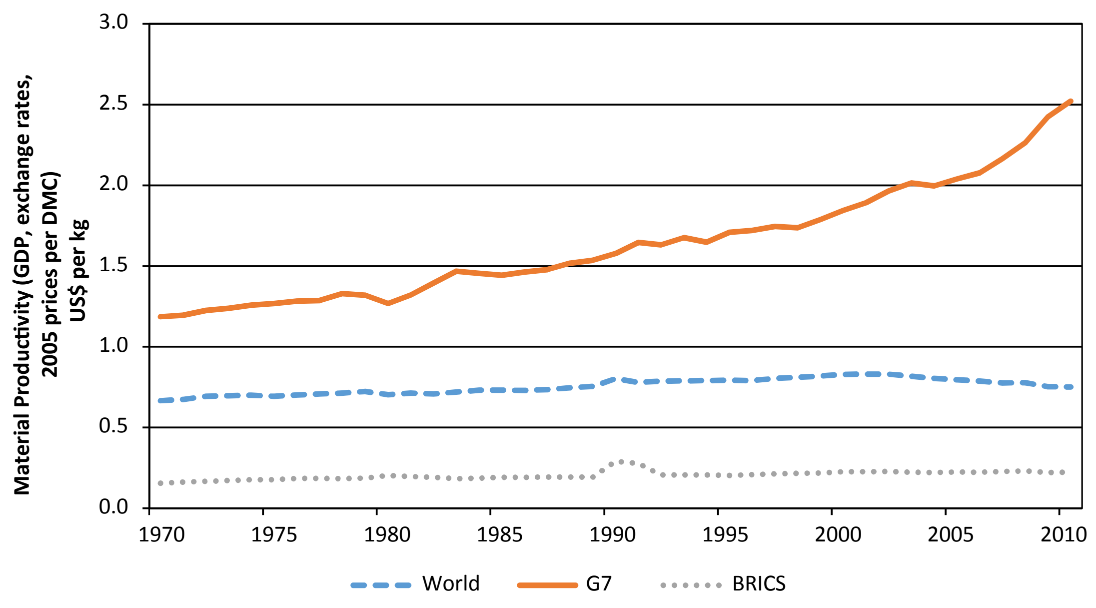
scale – through changes in technology (T). As noted in Part II - Chapter 1, successfully reducing I via changes in T entails a “double decoupling”, of economic development from resource use, and of resource use from environmental impact (BIO Intelligence Service et al., 2012). In this chapter, we discuss the main trends in resource productivity and resource intensity, two essential parts of the resource efficiency concept. Again, we address materials, land, water and energy separately.

2.1. Resource efficiency trends in materials use

As discussed in Part I - Chapter 2, there are various relationships between the physical tonnes of primary materials consumed, and the monetary value of products and services produced by an economy. This chapter focuses on the measure of material productivity (MP), calculated as US dollars ($) of GDP[7] per kg of DMC. As noted in Part I - Chapter 2, this measure is the inverse of material intensity (MI).

As economies mature, they typically become more efficient at converting materials into GDP (their material productivity increases, or their material intensity decreases), as their structure becomes weighted less towards material-intensive primary sectors, and more towards service sectors and/or higher value-added manufacturing processes, which have a much lower material intensity. Increasing the share of services often enables GDP to increase with little additional material use.[8] Over the last four decades, the G7 economies have seen a gradual improvement in their material productivity by an average of 1.9 percent per year. In 1970, the G7 group generated US$1.2 from 1 kg of materials on average (see Figure 31). By

Figure 31: Material productivity (MP) in the G7, the BRICS and the global economy, 1970–2010 in US$ per kg



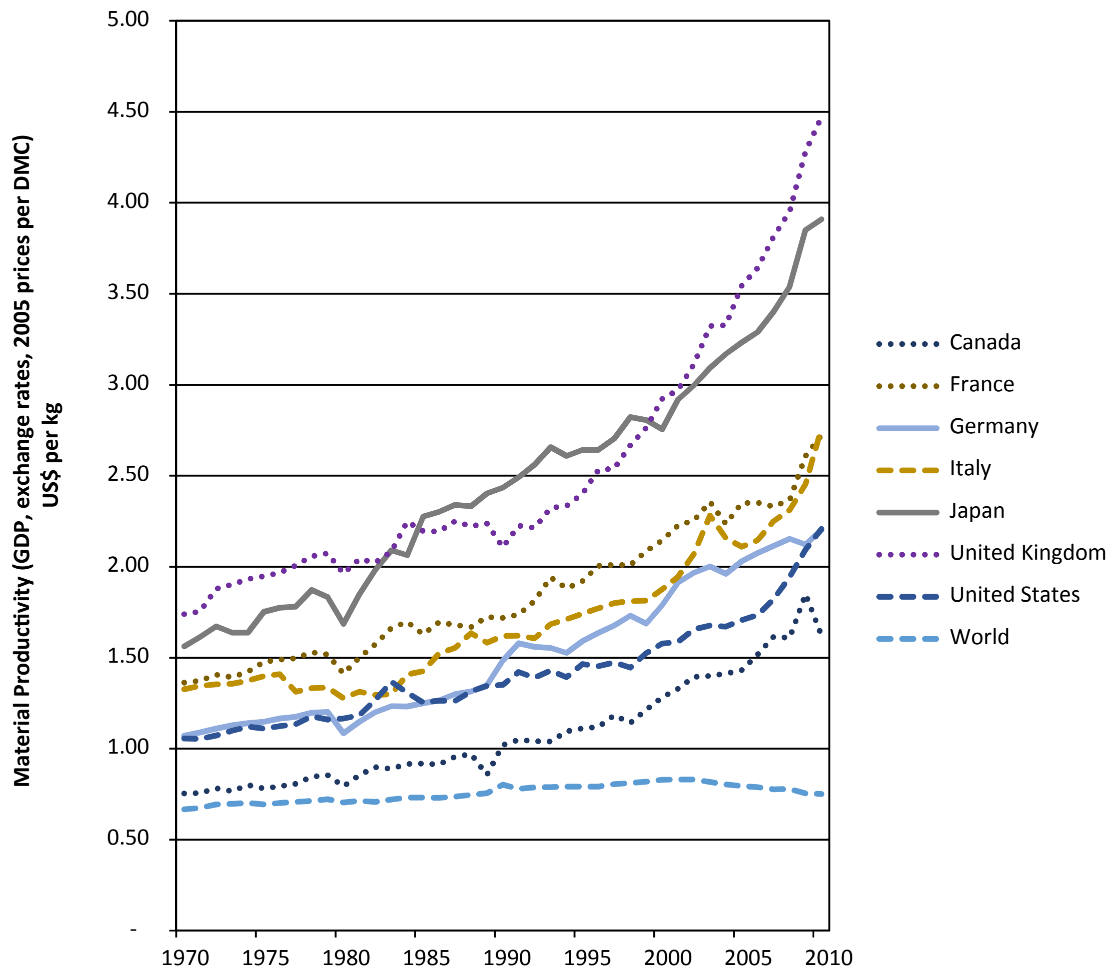
7 GDP is measured based on the exchange rate for US$, on a constant year 2005 basis.
8 This is especially so where the services are high value-adding, knowledge-intensive services such as banking, insurance, and technical services, which also tend to boost wages. The relationship will continue to hold, however, even where relatively low skill/wage services expand (e.g. tourism), as they still have relatively low material requirements.

2010, this had increased to US$2.5 per kg. The BRICS group of emerging economies required over seven times this volume of materials per dollar generated, making its MP substantially lower, although it did increase a little during this time period, from US$0.15/kg in 1970 to US$0.22/kg in 2010 (an annual improvement of 0.9 percent). Global material productivity from 1970 to 2000 remained practically constant. It increased very gradually until the year 2000 and subsequently declined.

Figure 31 shows the lack of an overall increase in global material productivity, despite the fact that many individual countries have increased their material productivity over time. This is the case for the individual G7 countries (Figure 32), and for most of the individual BRICS countries (Figure 33), as well as for most individual nations globally. Given this, the stagnation in aggregated global material efficiency reflects the large structural shift in the distribution of total global economic activity, away from the more material-efficient high-income economies, towards the less material-efficient emerging economies (Schandl and West, 2010).

As Figure 32 shows, the entire G7 group increased their MP over the full period. The large difference that remains between the most efficient member (United Kingdom), and the least efficient

Figure 32: Material productivity (MP) in G7 economies and the global economy, 1970–2010, in US$/kg

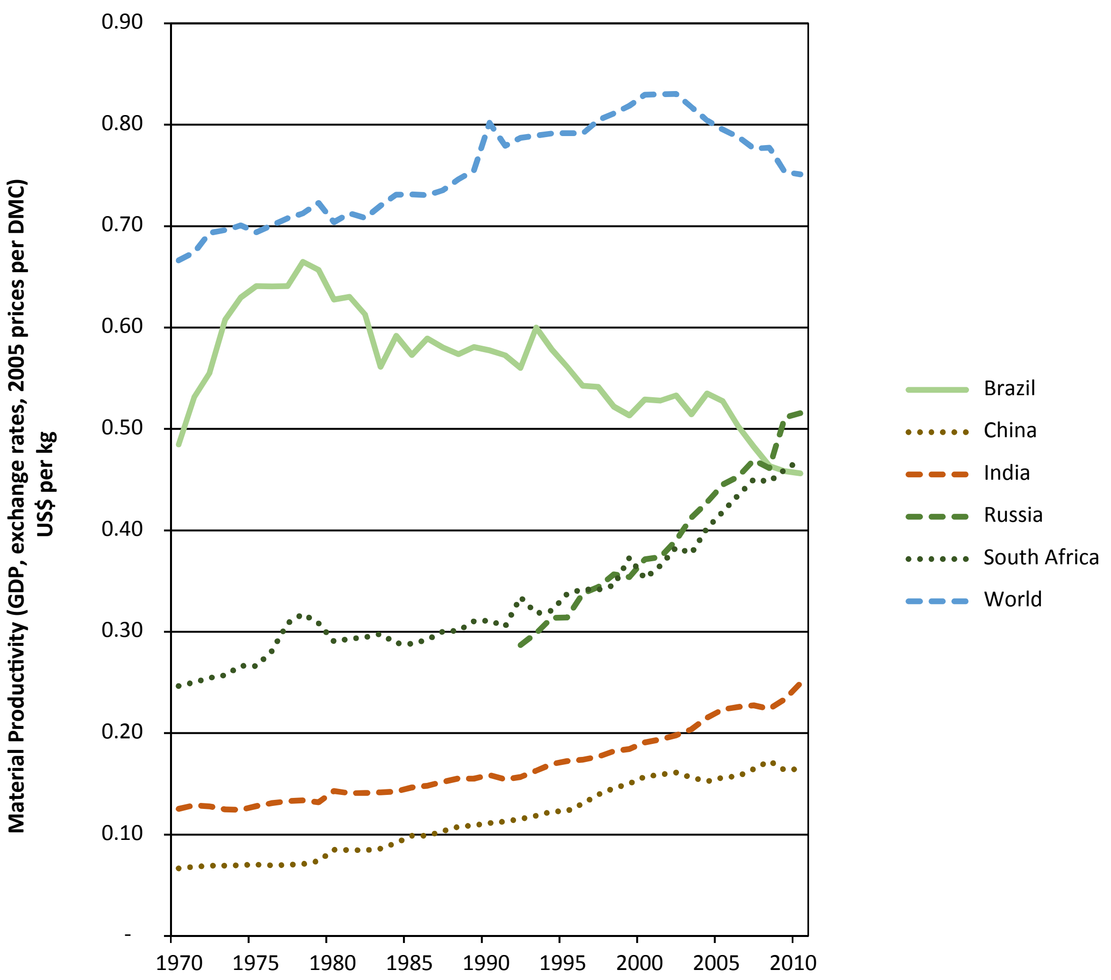


member (Canada) can be largely explained by the former having lost or otherwise offshored most of its material- and energy-intensive industries, while Canada remains a major producer of primary materials for export.

Figure 33 also shows the general pattern of improving material productivity (MP) for the individual countries in the BRICS group, with the sole exception of Brazil. The trajectory of China is striking, with an improvement of 2.3 percent per year compounding over the full period, so that by 2010 China was more than twice as efficient at generating income from materials as it had been in 1970. This dramatic improvement has global ramifications, given the rise of China to be the world's largest manufacturing power. However, at around US$0.16 per kg in 2010, China's MP is not even one tenth of that of the US, the world's former major manufacturer. This, of course, does not only reflect differences in technical efficiency – it relates as much to labour costs, standard of living and exchange rates.

Despite the steadily increasing MP of the G7 countries, and of several of the BRICS countries, Figure 32 and Figure 33 show that MP on a global basis has declined since 2000. This indicates that decreases in MP in other countries outweigh the growth in those featured here. The

Figure 33: Material productivity (MP) in BRICS economies and the global economy, 1970–2010, in US$ per kg



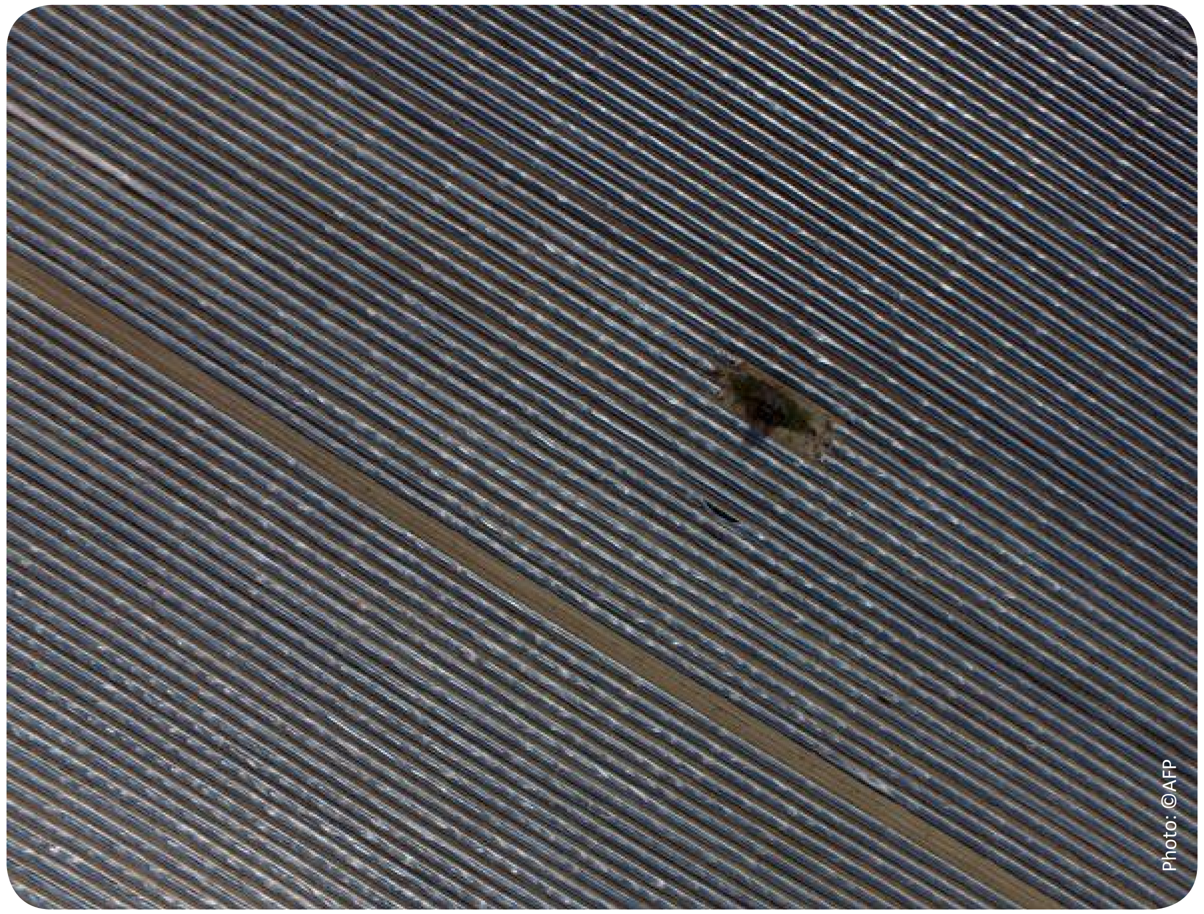
Part II: Resource efficiency: trends, economics and governance

trajectory of Brazil, as the one country shown here where MP decreased consistently over most of the study period, merits further examination. During the 1970s, its material efficiency actually improved quite rapidly, yet this ended and MP has been stagnant or decreasing ever since. One possible explanation for the initial strong improvement is that at that time, Brazil (in common with many Latin American countries) was following a development model based on state-led industrialization, in part oriented towards import-replacement manufacturing, often funded by petro-dollar loans. A growing debt burden rendered this model unsustainable, hence it was increasingly discarded and replaced by primary export-oriented policies, aimed at generating the trade surpluses required to repay debt (Bértola and Ocampo, 2012). In Brazil's case, another action that greatly expanded DMC was the decision to replace a significant proportion of the nation's fossil fuel requirements with biomass. This required that very large tonnages of low-energy-density biomass be produced to replace much smaller tonnages of fossil fuels (West and Schandl, 2013). This large increase in biomass, especially in relation to fossil fuels, is in fact a very unusual development, and runs counter to the path of socio-metabolic transitions, as set out in Fischer-Kowalski and Haberl (2007).

Innovations and targeted measures have increased material productivity in a range of different countries and sectors. Specific examples of these are discussed throughout Part III of the report (Chapters 1–7), particularly in Chapter 2, which examines reducing, reusing and recycling materials and products, and Chapter 3, which considers resource-efficient urban systems.

2.2. Resource efficiency trends in land use

Global production of primary crops more than tripled from 1961 to 2013 (FAO, 2016a), while global cropland area increased by only around



Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

14 percent (FAO, 2016a). This was made possible by steady increases in land productivity, which in turn were delivered by substantial increases in agricultural inputs. As shown in Figure 34, the area of cropland equipped for irrigation doubled over the period, with the application of fertilizers increasing by around five times. Pesticides are also a significant input — their application grew almost three times between 1990 and 2011 (FAO, 2016a).

Although this productivity increase has been important to support a necessary global expansion in food production, it is not without its challenges. Fertilizer inputs are finite and geographically concentrated resources, and continued high production may result in resource shortages and price rises (BMUB, 2015, Senthilkumar et al., 2014). The extraction and use of agricultural inputs also creates environmental impacts. The extraction of fertilizer inputs such as phosphates can create pollution through the release of heavy metals and radionuclides (BMUB, 2015). The production of fertilizers is energy-intensive and generates energy-related CO_2. In addition, the increased application of nitrogen and phosphorus fertilizers has resulted in considerable nutrient pollution, including eutrophication, increases in atmospheric ozone, fine particulate matter, acidification of surface waters which contributes to biodiversity loss, and greenhouse gas (GHG) emissions due to the production of N2O (UN Environment, 2014a). Pesticides, fungicides and bactericides, which have grown in use substantially since 1990 (FAO, 2016a), also have negative environmental impacts, particularly on biodiversity.

Intensive land use can also degrade the “productive capacity” of the land itself, as well as its environmental quality (UN Environment, 1997). The main causes of land degradation are water erosion, wind erosion, nutrient mining, water logging and salinization caused by irrigation, lowering of the water table, soil pollution as a result of over-use of chemical inputs, soil compaction and loss of organic matter (Scherr, 1999, FAO, 2015d). Globally, FAO considers about 25 percent of all land to be highly degraded or with a high degradation trend, 8 percent to be moderately degraded with a moderate degradation trend, while 36 percent is slightly or moderately degraded but stable. Only 10 percent of land is improving (FAO, 2011c).Furthermore, it is not clear whether increasing the application of fertilizers and pesticides can continue to increase yields indefinitely. There is evidence that yields for cereals are increasing at a slower rate than in previous decades, and experts expect yield growth rates to continue to slow (von Witzke et al., 2008, Bruinsma, 2009, UN Environment, 2014a).

As discussed in Part II - Chapter 1, UN Environment (2014a) focuses on cropland expansion, and considers — in addition to food demand — other pressures including increasing demand for biofuels and biomaterials, and loss of land to the built environment and to soil degradation. UN Environment (2014a, p. 68) estimates that from 2005 to 2050, current trends would lead to a gross expansion of 320–849 Mha (an increase of 21 to 55 percent) of global cropland.[9] The contribution of different drivers to this projection of cropland expansion is shown in Figure 35.

The UN Environment’s estimate of the “safe operating space” for land only allows cropland expansion of up to 1,640 Mha. This represents an expansion of 140 Mha, or a 10 percent increase from the 2005 cropland area used as the baseline for the study. With more recent FAO statistics suggesting that cropland now covers around 1,580 Mha (FAO, 2016a), it is clear that the scope for further growth within the “safe operating space” is very limited. This makes increasing resource efficiency in land use critically important, while simultaneously avoiding the negative impacts associated with the rising use of fertilizers, pesticides and

9 *Net expansion of cropland* results from rising demand for food and non-food biomass which cannot be compensated by higher yields. *Gross expansion* includes also the shift of cropland to other areas due to losses by severe degradation – in particular by soil erosion – and built-up land.

Part II: Resource efficiency: trends, economics and governance

Figure 34: Growth in cropland, agricultural inputs and crop yields, 1961–2013. Index: 1961=1

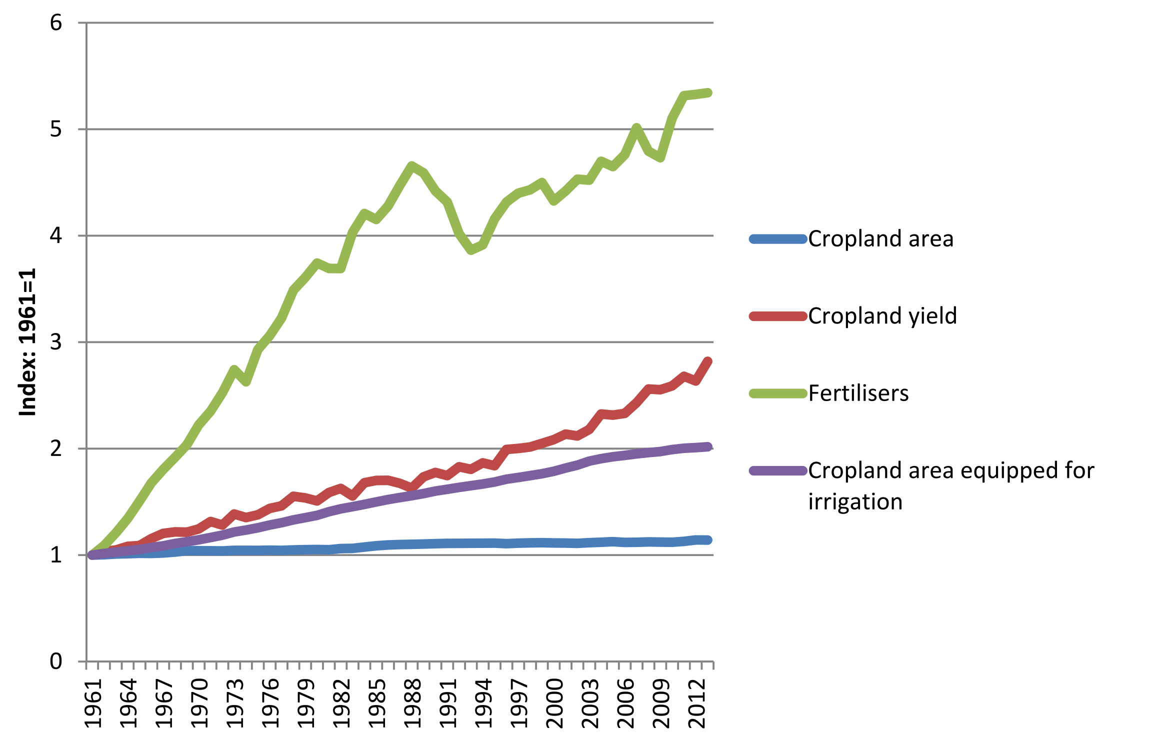
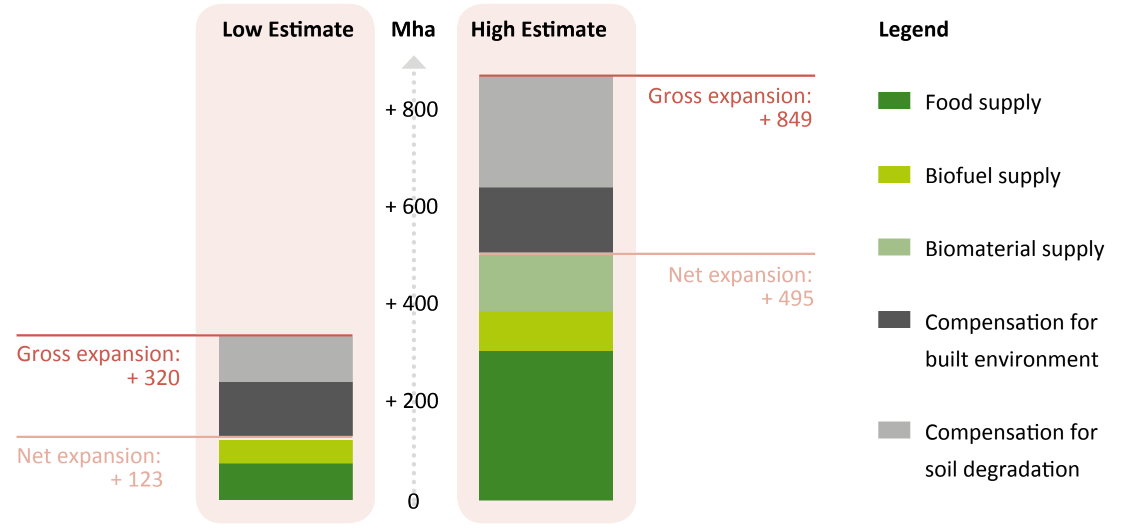


Figure 35: Trend of global cropland expansion from 2005 to 2050 for satisfying food demand and compensation of soil loss



Source: UNEP (2015c) p. 4.

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

other agricultural inputs. Specific examples of measures that have been taken to increase resource productivity in land use are discussed throughout Part III of the report (Chapters 1–7), particularly in Section 1.2.6 and Chapter 4, which examine sustainable food systems, and Part III - Section 7.2, which considers land degradation and restoration.

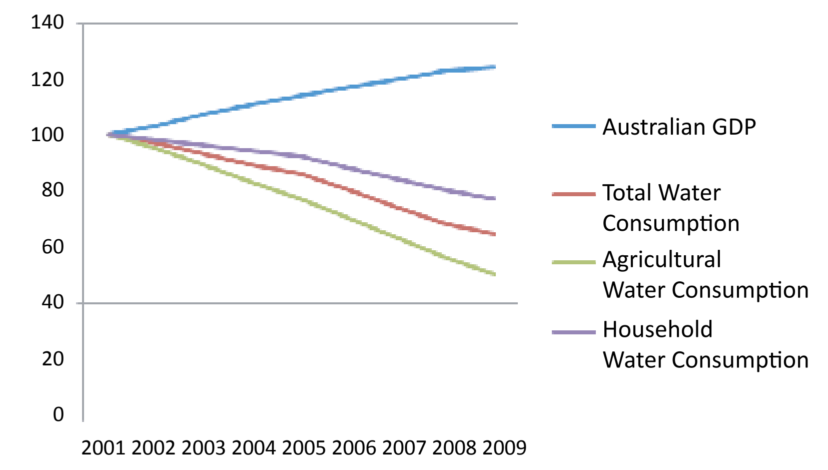
2.3. Resource efficiency trends in water use

As described in Part II - Section 1.3, water stress is already a key issue in many parts of the world. With projections of increased future demand, as well as possible threats to regional water availability arising from climate change impacts, countries in many parts of the world are right to be concerned about water scarcity. Improving the efficiency of water use will be critical to avoiding the worst outcomes of such projections.

There are examples of relative and absolute decoupling of water use from GDP, especially in countries and cities in which water shortage and scarcity are issues of concern. As shown in Figure 36, between 2001 and 2009, Australia's GDP grew by 30 percent, while its water consumption reduced by around 40 percent. This was achieved at negligible cost, through cost-effective measures in water efficiency and demand reduction (UN Environment, 2014b). As shown in Figure 37, in Singapore between 1965 and 2007, GDP grew by 25 times, whereas water consumption grew only fivefold. The average Singapore home now consumes four times less water than a US household of comparable income. Such efficiency was achieved through demand reduction, cutting waste and improving efficiency (UN Environment, 2014b). In China too, freshwater consumption has levelled off since 1998, while GDP has continued to rise (UN Environment, 2011b) (Figure 38).

In these and other countries, resource-efficient interventions in water consumption and use have taken a variety of forms. Specific examples will be reviewed in Part III of the report (Chapters 1-7), particularly Chapter 3 which looks at resource-efficient urban systems, and in

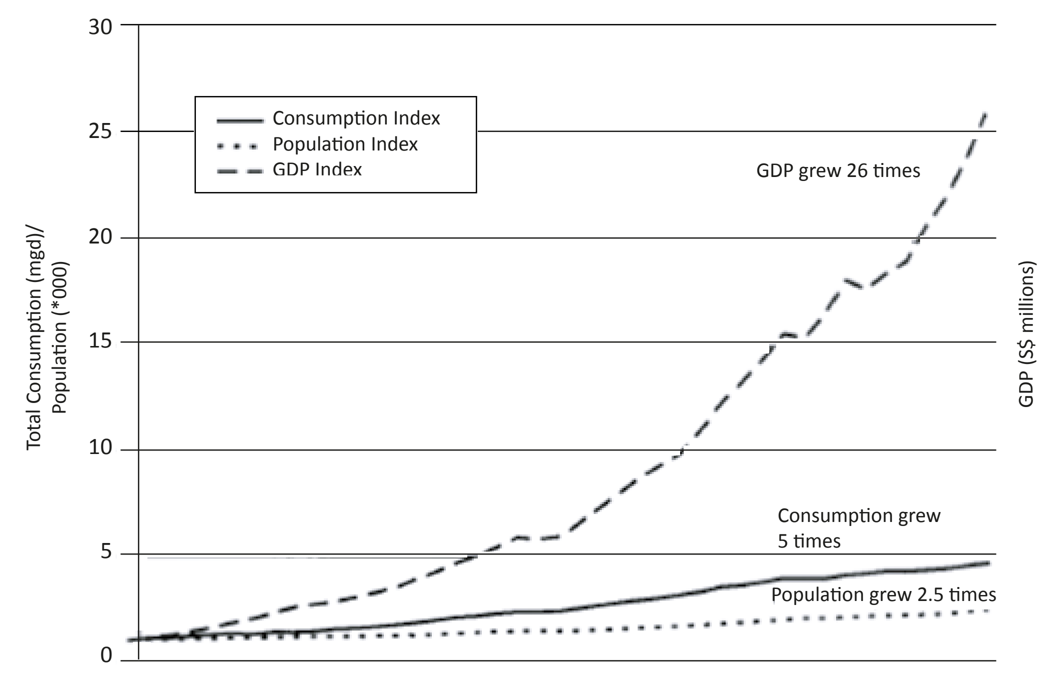
Figure 36: Australia – absolute decoupling of economic growth from freshwater abstraction [100=2001 levels]



Source: UNEP (2014b).

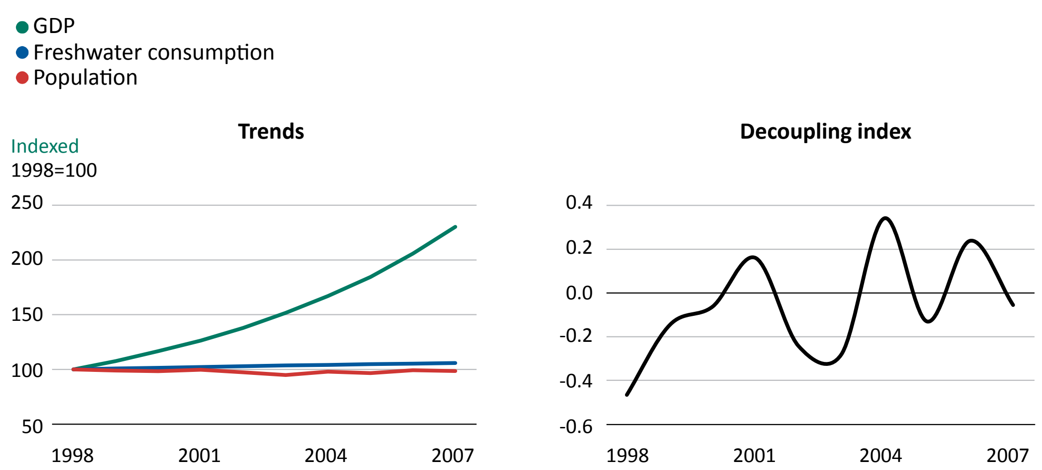
Part II: Resource efficiency: trends, economics and governance

Figure 37: Singapore GDP, population and total water consumption growth (1965–2007) [1965=1]



Source: UNEP (2014b).

Figure 38: Trends (left) of freshwater consumption, GDP and population in China; and the decoupling index (right) of freshwater consumption from GDP growth in China



Source: UNEP (2011b).

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

Part III - Section 7.1 within three sectors: agriculture, municipal and industrial/commercial.

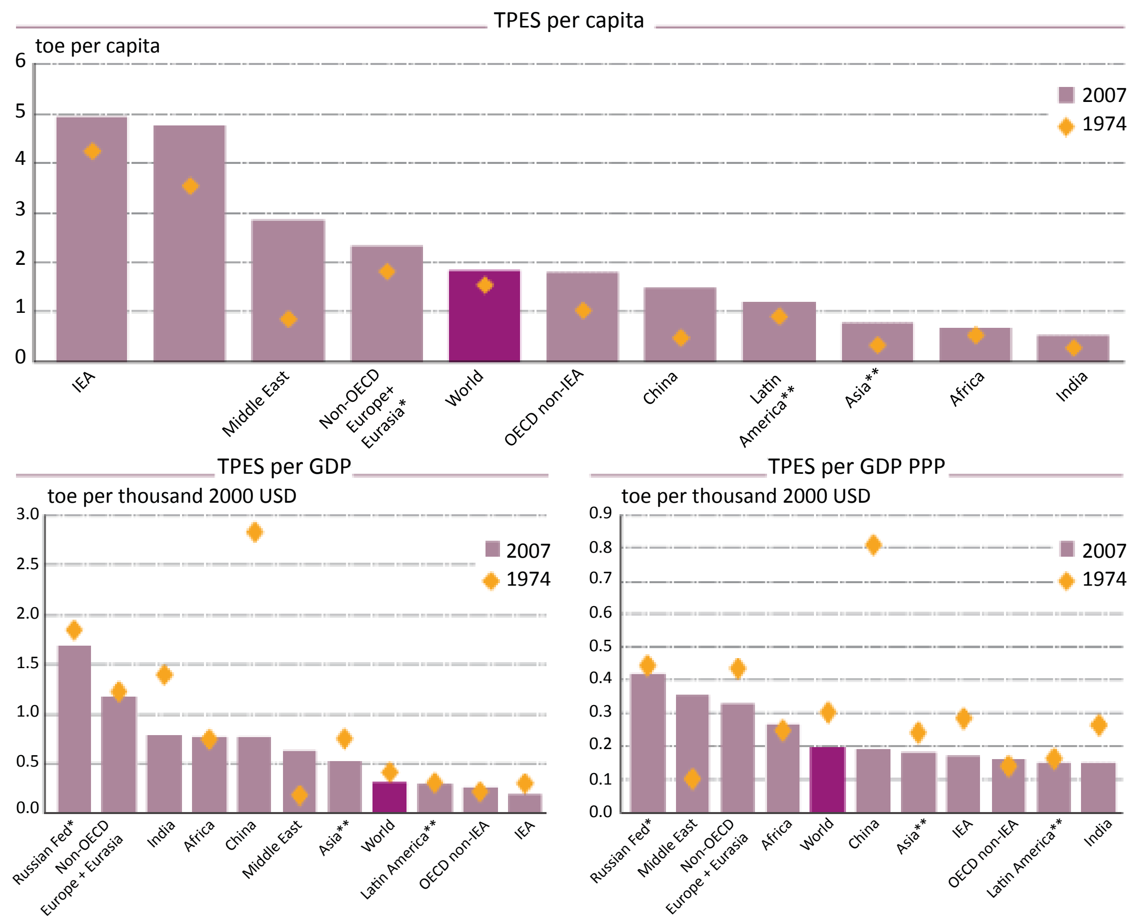
2.4. Resource-efficiency trends in energy use and GHG emissions

According to the Intergovernmental Panel on Climate Change (IPCC), scenarios in which it is "*likely*" that the global temperature will rise less than 2°C above pre-industrial levels "are characterized by atmospheric concentrations in 2100 of about 450 ppm CO_2eq". Such scenarios require global GHG emissions in 2050 to be 40–70 percent lower than in 2010, and for GHG emissions to be "near zero Gt CO_2eq or below in 2100" (IPCC, 2014d). In order to achieve the emissions reductions consistent with a 450 ppm scenario, the large-scale deployment of low-carbon technologies in energy and land-use systems will be critical. This has been explored in detail in numerous scenarios by the IPCC and others (IPCC, 2014d, IEA, 2010c, IEA, 2012a). Such work has led to climate policies focusing on renewable energy technologies, enabling the energy system to continue growing while the environmental impacts can be reduced at the same time, in effect decoupling energy use from fossil fuels. However, in addition to technological substitution, demand reduction — especially through increased energy efficiency — is recognized as having a crucial role in reducing GHG emissions. The IPCC states that "efficiency enhancements and behavioural changes, in order to reduce energy demand compared to baseline scenarios without compromising development, are a key mitigation strategy in scenarios reaching atmospheric CO_2eq concentrations of about 450 to about 500 ppm by 2100 (*robust evidence, high agreement*)" (IPCC, 2014d). Among such scenarios, the median level of demand reduction relative to baselines in the transport, buildings and industry sectors is between 20 and 30 percent in each case. Some of the scenarios analysed show even higher sectoral demand reductions of up to 60 percent (IPCC, 2014d). Increasing resource efficiency is critical to achieving such necessary demand reductions, without negatively affecting human development and well-being.

In the light of this conclusion, the International Resource Panel sent 10 Key Messages on Climate Change to the COP21 climate summit in Paris. These messages collectively stressed the need, if climate policy is to be successful, to decouple economic growth from environmental and resource degradation. The International Resource Panel concluded in its Key Messages to COP 21 that: "Raising resource productivity through improved efficiency and reducing resource waste … can greatly lower both resource consumption and GHG emissions. Such measures also confer additional, highly desirable social benefits such as more equitable access to resources and invaluable environmental gains such as reduced pollution. Decoupling economic growth and human well-being from resource use has, therefore, to be an integral part and prime concern of climate policy" (UN Environment, 2015c).

The efficiency with which energy is used to provide services to the economy can be considered by comparing the ratio of energy supply to the production of GDP, or the energy intensity of GDP. Energy intensity (measured as total primary energy supply (TPES) per dollar of GDP) has been improved in almost all parts of the world, especially when using figures of GDP expressed in Purchasing Power Parity (PPP) terms. Since 1974, China has seen a dramatic reduction of energy intensity in its economy. Other countries' improvements have been less dramatic, but still significant. For example, both India and the IEA group of countries approximately halved their energy intensity on a PPP basis from 1974 to 2009 (Figure 39). Growth in GDP itself is, of course, an important driver in reducing the energy intensity of GDP, and this will have been a significant factor for rapidly developing countries during this period. In countries that were already highly industrialized by 1974, the reduction in energy intensity may well have been driven by efficiency improvements and structural changes in the economy — moving away from energy-intensive heavy industry and manufacturing — as much as by rising GDP (IEA, 2011).

Figure 39: Total primary energy supply ratios in world regions, 1974 and 2009

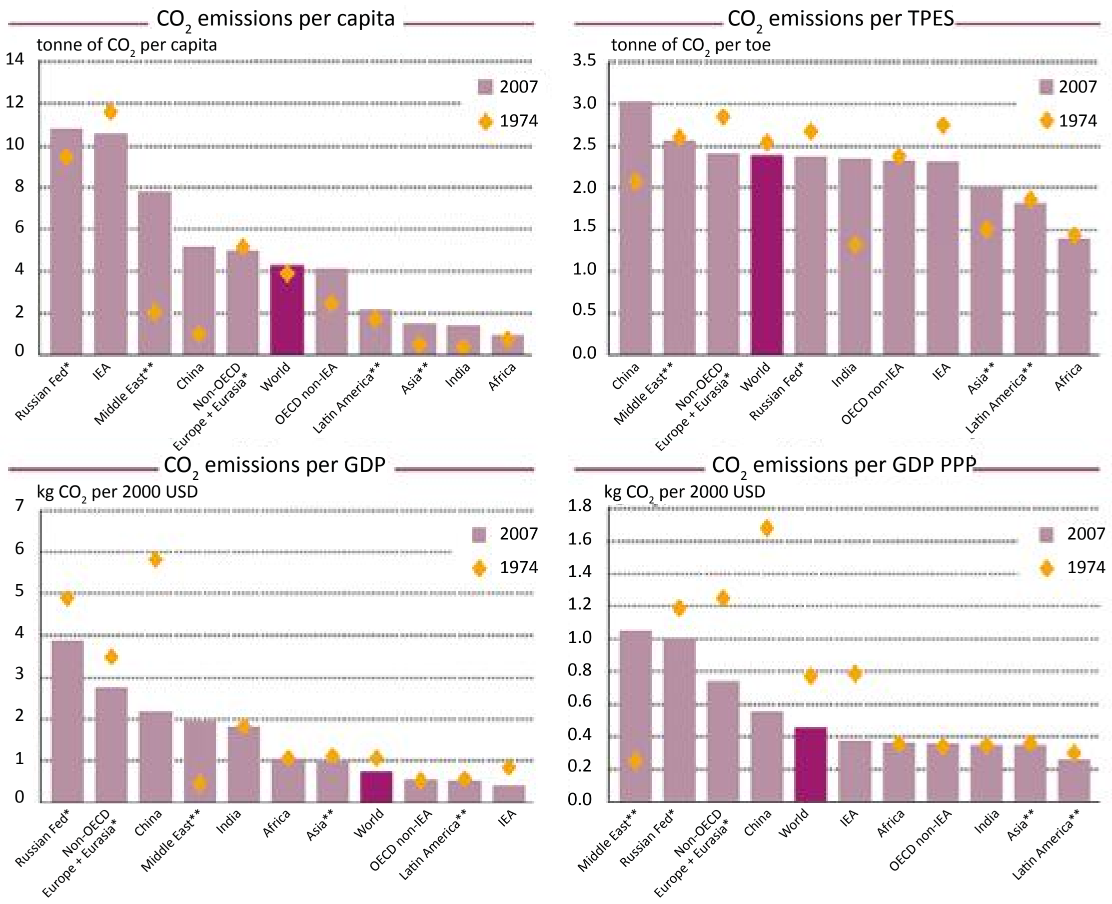


Note: OECD non-IEA countries are Chile, Iceland, Israel, Mexico and Slovenia.

Source: IEA (2011).

The trends in CO_2 intensity and productivity are quite similar to those of energy use (IEA, 2011). Global CO_2 emissions per capita have slightly increased over the period 1974–2009, with a huge increase in China. In some more developed countries, CO_2 emissions per capita have fallen, reflecting technological efficiency but also economic restructuring. CO_2 emissions per unit of TPES have been slightly reduced at the global level, indicating an overall improved eco-efficiency of energy production. Nevertheless, in rapidly developing countries such as China and India, CO_2 emissions per unit of TPES have increased, reflecting their development through heavy industry and manufacturing, powered largely by fossil fuels, especially coal. CO_2 emissions per GDP have fallen over the same time period, in almost all parts of the world, pointing to increased energy productivity. As with the energy intensity of GDP, a dramatic fall in the CO_2 emissions intensity of GDP was seen in China. However, the fact that the CO_2 intensity of energy increased in China over the period suggests that the reduction in the CO_2 intensity of GDP was due to substantially rising GDP, rather than to cleaner or less pollution-intensive energy.

Figure 40: Carbon dioxide emission ratios, 1974 and 2009



* For 1974, the Russian Federation includes the rest of Former Soviet Union (FSU). For 2009, Non-OECD Europe and Eurasia excludes Estonia, Slovenia and the Russian Federation.
** Middle East excludes Israel. Asia excludes China, India and OECD Asia Oceania. Latin America excludes Chile and Mexico.

Source: IEA (2011).

Specific examples of measures that can be taken to increase energy efficiency are discussed throughout Part III (Chapters 1-7). In particularly, Chapter 3 considers resource-efficient urban systems, Chapter 5 resource-efficient mobility, and Chapter 6 resource-efficient electricity systems.

2.5. Conclusions

In the period 1970–2010, G7 countries have demonstrated strong and consistent increases in material productivity, when this indicator is calculated as the output of GDP per tonne of material directly used by the economy. Most of the BRICS countries (with the exception of Brazil) also show material productivity improvements. However, the material productivity of these countries remains substantially lower than G7 countries.

Measured on a DMC basis, material productivity in some countries can appear to increase as a result of economic restructuring that moves away from heavy manufacturing and towards service-sector activities, instead importing manufactured products from other economies. This effect can be seen, for example, in comparing the material

productivity of Canada, which remains a large producer of raw materials, and the UK, which has to a greater extent offshored these activities and rebalanced towards services. This effect also helps explain the strong growth in DMC-based material productivity of the G7 countries, and for most of the BRICS countries, compared with the lack of growth in this measure for the world as a whole. G7 countries' increase in material productivity has in many cases been achieved through the offshoring of heavy industry to countries with lower production efficiencies. This allows G7 countries to increase their material productivity on a DMC basis, but actually induces the opposite effect for material productivity of the world as a whole, as shown by the declining global MP since 2000 (Figure 31). This overall effect can also be seen in Figure 13, Part II - Chapter 1, which shows global material extraction to be increasing at a faster rate than GDP since 2000. Thus, the recent fall in overall global material productivity occurred because of a global shift of production from countries with high material productivity to countries with much lower material productivity. Apparent increases in material productivity for individual countries must therefore be examined in the context of global trade, as they may sometimes involve service-based economies simply "exporting" the material and environmental burden of their consumption (UN Environment, 2015d).

Over the last 50 years, dramatic increases in land productivity have enabled crop production to more than triple, while the global cropland area has increased by only 14 percent. However, this significant productivity increase has been enabled by increases in the use of water, fertilizers and pesticides, which are themselves subject to resource constraints and can cause environmental impacts. Continuing to increase land productivity, while reducing the environmental impacts associated with the extraction and use of agricultural inputs, will be a major challenge.

Water scarcity is a serious concern in many parts of the world, and projections suggest that the continuation of current trends in the extraction of water for municipal, industrial and agricultural uses will create severe water stress for large numbers of people. Examples of more efficient use of water are however available, especially in locations in which water stress is particularly apparent. China and Singapore have dramatically decoupled water use from GDP in recent decades, and Australia achieved absolute decoupling of water use from GDP in the 2001–2009 period.

Energy productivity — measured as total primary energy supply per GDP (PPP) — increased worldwide in the 1974–2009 period. The most dramatic increase was seen in China, due largely to the explosive growth of its GDP during the period. More modest improvements can be seen in IEA countries, which may be attributed to economic restructuring as well as technological change. In the same period, the carbon intensity of energy decreased very slightly at the global scale. Most improvement has taken place in developed countries, due to technological change and energy efficiency measures, while in emerging economies such as China, the CO_2 intensity of the energy system has risen considerably. This confirms that the dramatic energy productivity increase in China is the result of an explosive growth of GDP, and less so of energy efficiency innovations.

Referring back to the IPAT equation, the increase of the P and A factors is not compensated sufficiently by the T factor in terms of increasing resource efficiency. There are some signs that when a certain level of economic output is reached, the demand for materials and energy per capita will stabilize as well. In the meantime, pending a stabilization of the world population, increasing resource efficiency remains a very important path to follow. The extent to which the T factor — in the form of technological and social innovations to increase resource efficiency — can do more to mitigate the pressures on planetary boundaries caused by rising population and affluence is explored in subsequent chapters. Specific examples of measures that can be taken to increase resource efficiency are discussed throughout Part III (Chapters 1-7).

3. THE ECONOMICS OF RESOURCE EFFICIENCY

Part I - Chapter 2 introduced some of the basic ideas related to the economics of resource efficiency. In particular, it made a distinction between resource efficiency in physical and monetary terms, which can explain why increased resource efficiency may not increase economic efficiency. It also introduced the idea of external costs related to resource use, the appropriate internalization of which will always increase both resource efficiency (or reduce any associated negative environmental impacts) and economic efficiency. The latter will only be apparent in monetary terms if the increased resource efficiency or reduced environmental impacts have been expressed in monetary terms. Chapter 2 also distinguished between the microeconomic and macroeconomic costs and benefits of increasing resource efficiency. This chapter explores these issues in more detail, although it is limited to the economics of resource *efficiency*, rather than of resources and economics more generally. Many issues of environmental and resource economics, such as the discount rate, property rights, environmentally perverse subsidies, or broader environmental and resource policies, are therefore referred to only in passing. Similarly, Part II - Section 3.3 on the macroeconomic benefits of resource efficiency concentrates on comparing different macroeconomic approaches to modelling as they relate to resource efficiency, rather than being a treatise on modelling more generally.

3.1. The microeconomic costs and benefits of resource efficiency

There have been a number of estimates of the costs of increasing resource efficiency, with one of the most often cited shown in Figure 41. The y-axis shows the cost of increasing resource efficiency for the technologies concerned, while the x-axis shows the "resource benefit" (essentially the cost savings) in 2030 of implementing these technologies. It is immediately apparent that around US$2 trillion per year of cost savings could be achieved at negative cost by that date. For Figure 41 as a whole, Dobbs et al. (2011, p. 10) state that implementing all the technologies shown would save private investors US$2.9 trillion per year by 2030, with 70 percent offering a rate of return greater than 10 percent per year. The US$900 billion investment required "could potentially create 9 million to 25 million jobs. Over the longer term, this investment could result in reduced resource price volatility that would reduce uncertainty, encourage investment, and also potentially spur a new wave of long-term innovation" (Dobbs et al., 2011, p. 12).

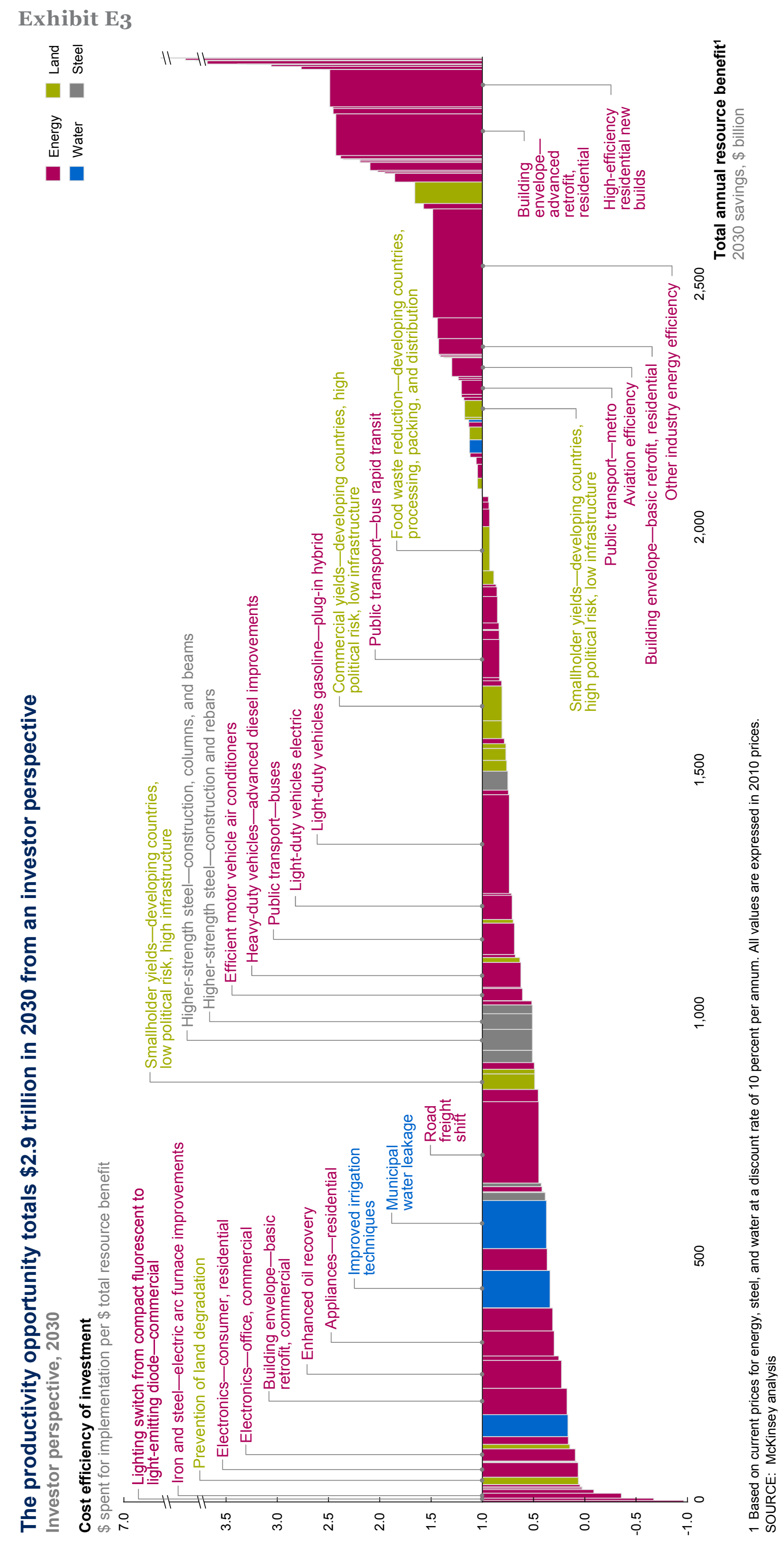
The authors are clear that these benefits have been calculated at the 2010 market prices of resources. As these prices — especially of fossil fuels — have since declined, the benefits of resource efficiency will be proportionally less.

Such negative cost opportunities for investments in resource efficiency raise the question as to why investors do not make the necessary investments to realize these benefits. Although this issue has been most extensively explored for energy efficiency, the arguments equally apply to other resources. Sorrell et al. (2004, pp. 25–93) provide a comprehensive explanation for the existence of an "energy efficiency gap": the difference between engineering-economic calculations of cost-effective energy efficiency opportunities, such as will have been employed to derive the energy-related technologies in Figure 41, and the actual implementation of energy efficiency measures in the real world. An analogous "resource efficiency gap" is therefore measured by all the negative cost entries in Figure 41.

Sorrell et al. (2004, pp. 32–33) first identify the efficiency gap as the product of three phenomena:

- *Market failure*, normally identified as a result of incomplete property rights, positive and negative externalities, imperfect competition and asymmetric information

Figure 41: The potential microeconomic costs and benefits of illustrative resource-efficient technologies



Source: Dobbs et al. (2011), Exhibit 3, p. 13.

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

- *Organizational failure*, as a result of imperfect organizational structure and policy, and
- *Non-failure*, where organizations and individuals are in fact behaving rationally in not taking the efficiency opportunities, because of "hidden costs", i.e. costs that are experienced by the actors concerned, not uncaptured externalities.

They then extend the analysis into the areas of transaction costs and behavioural economics: the former covering issues of bounded rationality and costs of search and information, bargaining and decision-making, supervision and enforcement, and establishing and running organizations, and the latter adding the biases, errors and decision heuristics that are known to characterize real human behaviour. From these theoretical and empirical insights, Sorrell et al. (2004, p. 55) construct their "taxonomy of barriers to energy efficiency", which mixes market failure, organizational failure and non-failure and is summarized in Table 5.

IEA (2012b)(Table 9.2, p. 280) has a similar taxonomy of barriers to energy efficiency, which again can be applied to resource efficiency more generally:

Table 5: A taxonomy of barriers to resource efficiency

Barrier	Claim
Risk	Resource efficiency investments may have higher technical or financial risks, or involve greater uncertainty over returns, justifying shorter payback periods, than other investments.
Imperfect information	Makers of inefficient products have incentives to conceal information about resource efficiency. This may result in inefficient products driving efficient products out of the market and cost-effective opportunities for resource efficiency being missed.
Hidden costs	Resource-efficient technologies may not deliver the full range of performance utilities of other products. In addition, engineering-economic cost estimates may not account for all the costs associated with increasing resource efficiency, such as management and training costs, disruptions to production and the costs of gathering, analysing and applying information.
Access to capital	Access to capital for resource efficiency may be limited, and available capital may yield higher returns, or be perceived to do so because of internal accounting, appraisal and management procedures.
Split incentives	As with the common landlord-tenant relationship, the beneficiary of an investment in resource efficiency (often the tenant) may not be the economic actor who needs to make the investment (the landlord). The latter may therefore not have the incentive to do so.
Bounded rationality	Individuals experience constraints on time, attention and the ability to process information, which may cause them to overlook resource efficiency opportunities, even given good information and appropriate incentives.

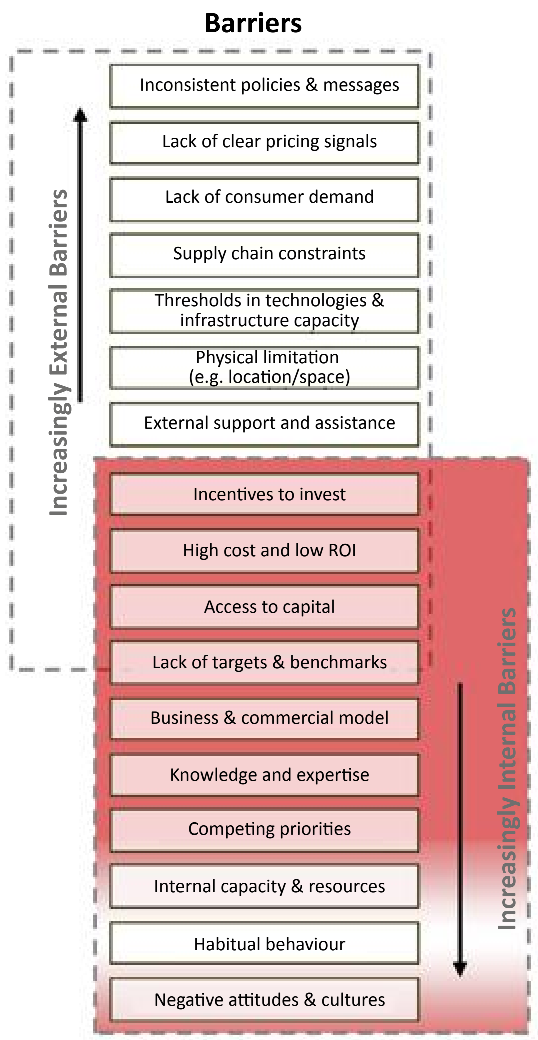
Source: adapted from Sorrell et al. (2009), Table 5.2, p. 55.

- Lack of visibility, so that efficiency opportunities are not known to exist
- Lack of priority, so that efficiency measures are undervalued
- Economic issues, such as those mentioned above, including split incentives, lack of access to capital, perceived riskiness and the subsidization of resource use
- Lack of capacity, involving limited knowledge about resource efficiency measures and how to support their implementation
- Fragmentation of resource use among different uses, users, and supply chains, and supply-focused business models.

AMEC and BioIS (2013) identified both internal and external barriers to increased resource efficiency in businesses (Figure 42). The internal barriers largely reflect the organizational and behavioural issues identified by Sorrell et al. (2004). Meanwhile, the external barriers largely reflect Sorrell et al.'s (2004) category of market failures, where these have not been addressed by government policy.

The existence, strength and persistence of these barriers varies from issue to issue, and there are no magic solutions to overcoming them, through public policy or otherwise. Rather, attempts to improve resource efficiency requires painstaking analysis to understand the applicable barriers, before identifying and introducing measures to surmount them.

Figure 42: Barriers to businesses becoming more resource efficient



Source: AMEC and BioIS (2013), Figure B9, p. 83.

Even if there are microeconomic benefits from increasing resource efficiency, there may also be sectors or industries that suffer losses. It will be important to consider how these losses may be reduced or cushioned for affected workers or businesses. Two examples from Poschen (2015) show how different countries in very different circumstances have responded to these challenges. In China in the late 1990s, a serious drought and floods led to a reconsideration of forestry and farming polices. This resulted in a logging ban on nearly 70 percent of China's natural forested area, and 40 percent of all its forests, with severe social and economic costs that included around 1 million workers losing their jobs. The social effects were mitigated through a combination of retraining schemes, one-off compensation payments and associated assistance in setting up small businesses for around 680,000 redundant younger workers to help them adjust (Poschen, 2015) (p. 76)., and early retirement payments for older workers.

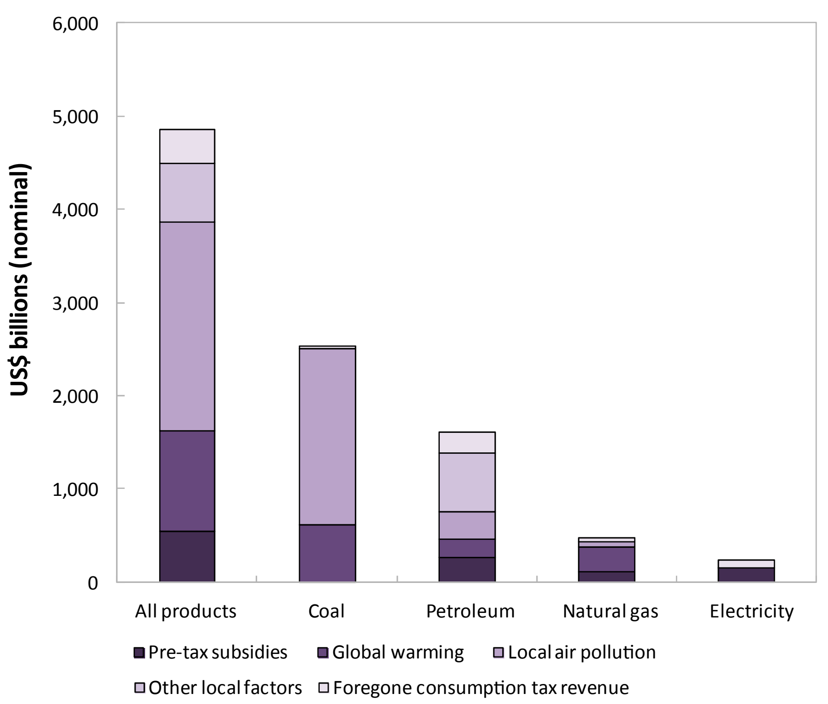
Another example relates to Norway's response to chronic overfishing and declining fish stocks, which resulted in all its major fisheries being effectively closed down by 2005. A Fishers' Guarantee Fund was set up to help fishers cope with loss of income, retrain them, and expand other activities including aquaculture, fish processing and non-fishing enterprises. Rural and regional policies emphasizing education, training and investment sought to address longer-term restructuring challenges. These efforts were able to manage a decline in employment affecting around 100,000 people in the industry, so that when fish stocks rebounded, the average income of fishers was substantially higher than it had been and former fishers had alternative employment (Poschen, 2015, p. 78).

3.2. The microeconomic benefits of reducing externalities

As already noted, the extraction and use of resources often results in negative external costs, especially in relation to the environment. Resource efficiency measures that reduce these external costs, by internalizing them into the costs of resource use or otherwise, will improve economic efficiency, over and above any other benefits (e.g. cost savings) in which they may result.

The environmental externalities of resource use, which may also be considered subsidies to that use, are very large indeed. According to Figure 43, showing the calculations produced by the International Monetary Fund (IMF), total fossil

Figure 43: Global subsidies by product and subsidy component, 2013



Note on figure: 'Other local factors' in Figure 5.3 apply only to petroleum products and refer to non-internalized externalities from congestion, accidents and road fuels.

Source: Coady et al. (2015), Figure 6, p. 22.

Part II: Resource efficiency: trends, economics and governance

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

fuel subsidies were US$4.9 trillion in 2013. These were projected to rise to US$5.3 trillion, or the equivalent of 6.5 percent of global GDP, in 2015.

In Figure 43, pre-tax subsidies are direct financial subsidies paid to producers and consumers. In 2013, they amounted to US$541 billion, of which only about 3 percent were producer subsidies. Around 50 percent of pre-tax subsidies in 2013 went to petroleum products, with the rest split between natural gas (21 percent) and electricity (29 percent). Pre-tax subsidies for coal were negligible.

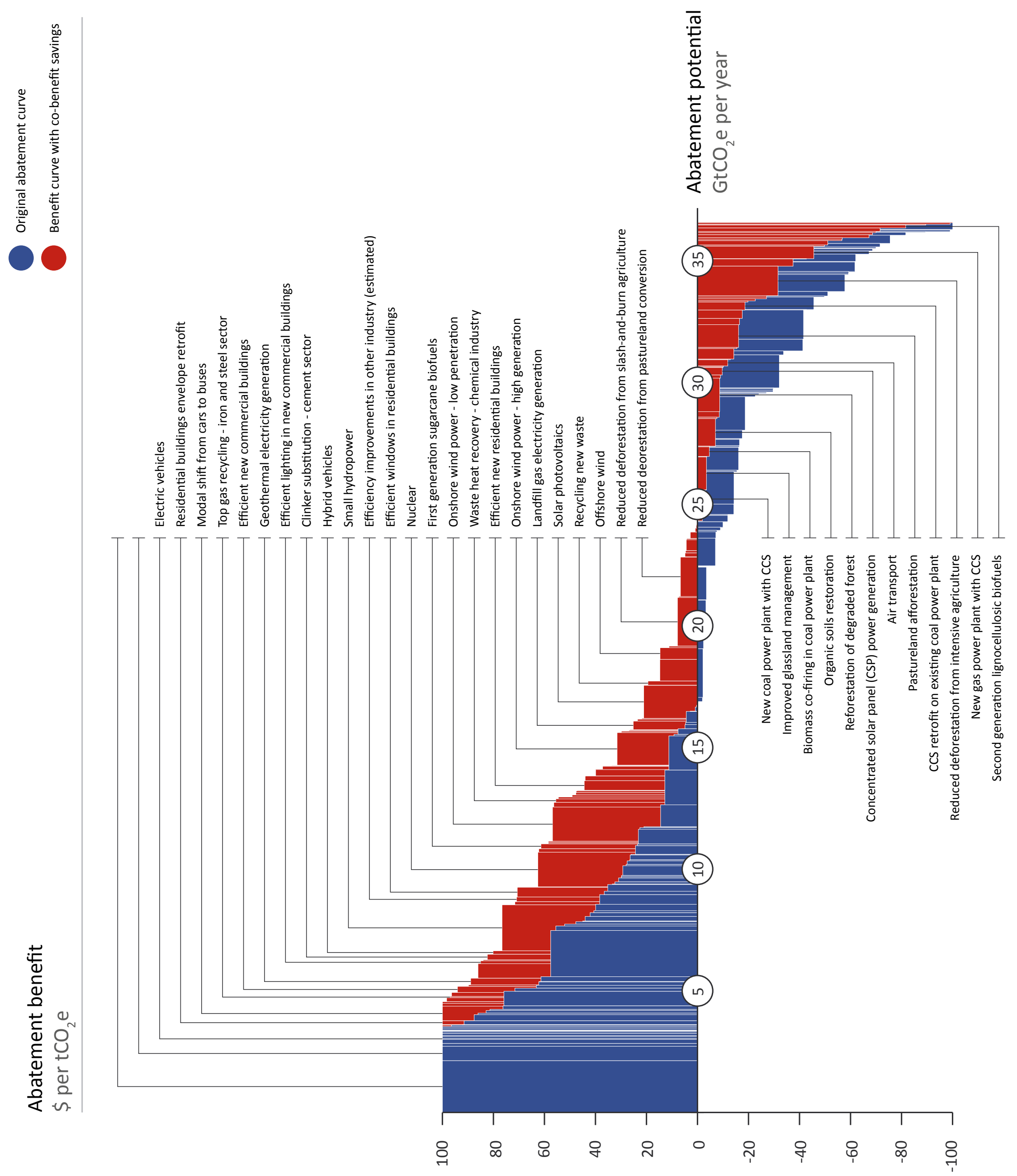
Figure 43 also shows that the subsidies relating to fossil fuels arising from uninternalized externalities (including global warming, local air pollution, and other local factors [congestion, accidents and road damage]) are much larger than the direct financial subsidies. Amounting to US$3.95 trillion in 2013, they were projected to rise to US$4.66 trillion in 2015. Increases in resource efficiency that reduce these subsidies, as well as achieving some of the cost savings shown in Figure 41, offer the best prospect for increasing both economic efficiency and human well-being. Coady et al. (2015, pp. 24–25) estimate that eliminating energy subsidies through efficient pricing of fossil fuels could reduce global consumption of natural gas by 10 percent, coal consumption by 25 percent, and the consumption of road fuels in those regions with the highest subsidies by up to 50 percent. The environmental benefits for human well-being include reducing CO_2 emissions by more than 20 percent and premature deaths from local air pollution (mainly from coal combustion) by 55 percent. In 2013, the global gain in economic welfare from eliminating fossil fuel subsidies is US$1.4 trillion, equivalent to 2 percent of global GDP. Most of this gain goes to the more than 50 percent of the world's population living in Emerging and Developing Asia, which experiences a welfare gain equivalent to 6.9 percent of regional GDP.

Much of this reduction in fossil fuel consumption could be achieved through an increase in energy efficiency, rather than a reduction in energy service delivery. Thus in its Efficient World Scenario, IEA (2012b) (p. 302) calculates that by 2035 "economically viable" energy efficiency measures could reduce global coal consumption by 22 percent, oil consumption by 13 percent and gas consumption by 14 percent. These are all below the levels in the IEA's New Policies Scenario, which had already achieved energy savings through energy efficiency of about 8 percent, compared with the Current Policies Scenario (IEA, 2012b) (Figure 9.4, p. 282).

Figure 44, which is similar in concept to Figure 41, shows how much larger the "negative cost" environmental improvement is when the reduction of externalities (which the figure calls "co-benefits") is taken into account. On the y-axis, the abatement benefit suggests that a little more than 15 $GTCO_2e$ of emission reduction per year can be achieved at net financial benefit (the blue bars). This increases to over 20 $GTCO_2e$ of net benefit emission reduction when the co-benefits (the red bars) are taken into account. Just as important, the right-hand side of the figure shows the extent, often by around 50 percent, to which co-benefits reduce the costs of the technologies that involve net financial costs.

Dobbs et al. (2011, p. 10) calculate that the savings to society from resource efficiency would increase from US$2.9 trillion from a private investor perspective to US$3.7 trillion from a social perspective if financial subsidies to energy, agriculture and water, and energy taxes were removed and carbon was priced at US$30 per tonne. Ninety percent of this US$3.7 trillion saving would yield an investment return of more than 4 percent (which is often taken as the social discount rate). They group their resource efficiency "opportunities" into 15 categories that capture approximately 75 percent of this US$3.7 trillion saving (Figure 45). Of these 15 categories, only electric and hybrid vehicles have a greater cost than benefit. Many of these categories and opportunities will be discussed in more detail in subsequent chapters of this report.

Figure 44: Marginal carbon dioxide abatement benefits curve for 2030



Source: NCE (2014), Figure 6, p. 43.

3.3. The macroeconomic benefits of resource efficiency

The discussion in this chapter so far has been of the microeconomic costs and benefits of resource efficiency. As noted in Chapter 2, these are very different from their macroeconomic implications.

In order to estimate these implications, macroeconomic models are required. These models seek to capture the full range of interactions within a macroeconomy, which normally relates to a country, group of countries or the world as a whole. Much of the discussion that follows relates to the macroeconomic impacts of increasing energy efficiency as a policy component for climate change mitigation. This is because far more work of this kind has been carried out in relation to energy than other resources. However, many of the arguments concerning the macroeconomic impacts of increasing energy efficiency are directly applicable to increasing resource efficiency more generally.

The few studies reviewed in this section have been chosen from the very large number in the literature because they show macroeconomic gains from implementing resource efficiency measures, and the economic mechanisms underlying the models that they employ are transparent. This enables the reasons for these gains to be understood and assessed. The models that have been used to investigate the economic impacts of increases in resource efficiency may be organized into three main categories: computable general equilibrium (CGE) models, macroeconometric models, and system dynamics models. This is not the place for a detailed discussion of and comparison between these different modelling techniques, but some explanation of them is necessary in order to understand their results when used to assess the economic implications of increases in resource efficiency.

Before comparing the different model types, one general point is worth making. The outcomes from the modelled scenarios of increasing resource efficiency are generally reported in relation to a baseline or reference case without the increased resource efficiency. The nature of these baselines may be as important to the reported results as the resource efficiency measures being modelled. The assumptions in the baseline may vary with the model type, as will be seen below, but relevant to all the model types are assumptions about resource and environmental impacts in the future.

The purpose of resource efficiency measures is to reduce risks of resource disruption and environmental damage (especially, but not only, from climate change). However, it is very rare that resource disruption and environmental damage are included in the baseline model run, hence the benefits of reducing these effects are routinely omitted from consideration of the economic implications of improved resource efficiency. Such omission is mainly due to the difficulties of including these effects, and the uncertainties surrounding them, in macroeconomic models. It should, however, be borne in mind when assessing the results of resource efficiency scenarios, compared to "business-as-usual" reference cases, that these results do not include the major resource and environmental benefits that provided the principal cause for their introduction in the first place. Were they to be included, the estimated resource efficiency benefits could be considerably greater.

3.3.1. Computable general equilibrium (CGE) models

CGE models are generally constructed on the basis of strong assumptions about clearing markets and rational, representative utility- or profit-maximizing economic agents. Nevertheless, they can start by reflecting market inefficiencies and market distortions, and then asking how policy reforms could be undertaken to achieve greater resource efficiency. In fact, CGE models have been widely used in the assessment of the macroeconomic gains of tax policy reforms or trade policy reforms.

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

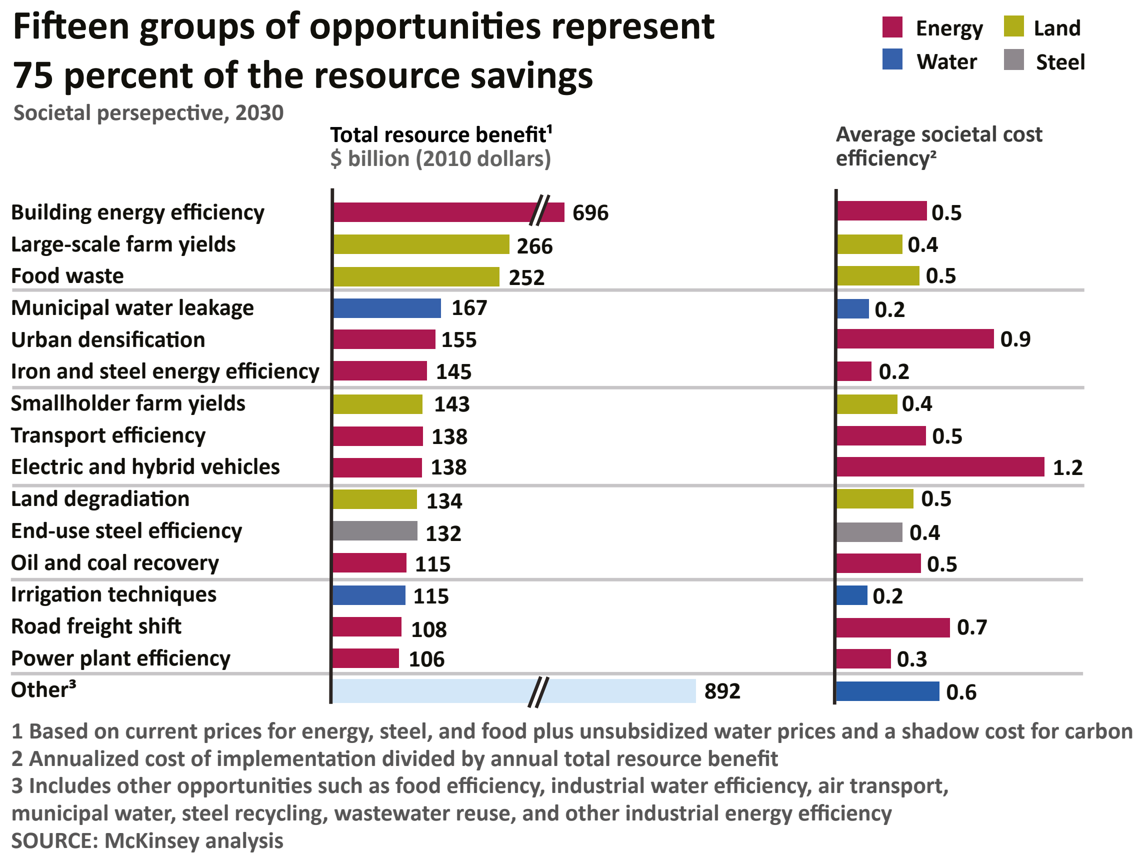
However, this has not always been the case in climate policy. As Stern writes in this connection in his New Climate Economy report (2014, p. 15): “These models often start from the assumption of an economy where resources are already efficiently allocated and there are no market failures.” Under these circumstances, economic efficiency is already at a maximum, and increased technical efficiency in the use of material or energy resources can only be achieved at a net economic cost. Stern continues: “But we live in an imperfect, inefficient and constantly changing world where there are multiple frictions, unemployment and other dynamics, and multiple unpriced benefits from climate policies such as reduced local air pollution, increased energy security and stronger biodiversity. Thus, the models often fail to capture these key features when simulating the GDP impact of climate policy on output.” As noted, Stern was writing about climate policy (those interested in his more detailed critique of modelling related to climate change may like to consult Stern (2013)), but precisely the same point could be made about policy that increases the efficiency of the use of energy or material resources.

CGE modellers are continuously trying to improve their models in order to gain more realistic insights into the possible economic implications of increases in resource efficiency. One notable example is the ENV-Linkages CGE model developed by the OECD. This was used by the IEA to model the economic outcomes of the policies in its Efficient World Scenario. IEA describes thus the outcome of its modelling exercise: “Our analysis shows that the economic impact of the Efficient World Scenario would feed through a number of channels. In general, the policies included in the Efficient World Scenario would encourage firms and households to shift their spending patterns towards more energy-efficient capital goods, which, in turn, reduces their expenditure on energy consumption. This change in the balance of spending, and therefore supply and demand, has a cascade effect on the relative price of all goods and factors of production in the economy. Firms producing less energy-intensive goods and services are faced with increased demand and react by trying to maximise profits. By contrast, demand for more energy-intensive goods and services declines. At a household level, the move towards less energy-intensive goods and services results in a reduction in energy expenditure, which boosts disposable income and increases spending elsewhere” (IEA, 2012b, Box 10.1, p. 314). The macroeconomic outcome of this exercise suggests that by 2035, global GDP in the Efficient World Scenario would increase by 0.4 percent compared with the IEA New Policies Scenario, with OECD Europe, the US, Japan, Korea, China and India benefiting more than this, but Russia and the rest of the world having reduced GDP (4.5 percent lower by 2035 in the case of Russia). In this case, the energy efficiency policies reduce energy demand and energy prices, benefiting energy-importing countries, but making energy exporters worse off.

A report on the circular economy from the Ellen MacArthur Foundation, in collaboration with the SUN Foundation and the McKinsey Center for Business and Environment (EMF, 2015), quoted the results of some CGE modelling related to three of the main sectors with resource efficiency opportunities that had featured in the earlier McKinsey report (buildings, food waste and transport; see Figure 45). The study found as follows: “The circular economy scenario could increase the disposable income of an average European household through reduced cost of products and services and a conversion of unproductive to productive time (e.g. reduction in congestion cost). This could result in increased consumption and thereby higher GDP growth. Economic modelling across the three study sectors suggests that today’s disposable income of an average European household could increase as much as 18 percent by 2030 and 44 percent by 2050 in a circular scenario, compared with 7 and 24 percent in the current development scenario.

“European GDP could increase as much as 11 percent by 2030 and 27 percent by

Figure 45: The top 15 categories of resource efficiency potential



Source: Dobbs et al. (2011), Exhibit 4, p. 14.

2050 in a circular scenario, compared with 4 percent and 15 percent in the current development scenario, driven by increased consumption due largely to correcting market and regulatory lock-ins that prevent many inherently profitable circular opportunities from materialising. Thus, in a circular scenario, GDP could grow with 7 percentage points more by 2030 than the current development path and could increase the difference to 12 percentage points by 2050.

“These results are higher than reported from most other recent studies on the economic impacts of a circular and resource-efficient economy. For instance, the recent report “Study on modelling of the economic and environmental impacts of raw material consumption” conducted by Cambridge Econometrics and BIO Intelligence Service [see below], concluded on a slightly positive GDP impact. The key reason for the difference is that this report assumes a slightly substantially [sic] higher pace of technology change in the big product and resource sectors going forward compared to what has been observed in the past — for the reasons explained above — whereas most other reports assume a similar pace as witnessed historically” (EMF, 2015, pp. 32–33).

However, in the Technical Report on the modelling the authors write: “[T]he bulk of multisector multi-region CGE models abstains from endogenous technological change and instead adopts the drastic assumption of autonomous technical progress which comes along as "manna from heaven". … The direct (partial equilibrium) economic effect of a technology shift in transportation can be directly calculated as the product of benchmark cost times the difference between the scenario-specific cost index and unity. … However, the interpretation of results should not be stretched too far. More specifically, the technology shifts are unconditional, i.e., the transition from the benchmark technology to the future technology is not explained endogenously. Technological change occurs as manna from heaven. *Thus, neither the simplistic partial equilibrium accounting nor the complex general equilibrium calculations can be credibly used to claim that technology progress is for free and will bring about larger GDP and economic efficiency gains* – the unconditional technology forecasting does not quantify the economic cost (e.g. in R&D) to achieve specific technological change nor the opportunity cost of foregoing other directions of technological change. Scenario assumptions on drastically reduced capital and fuel cost for private transportation are not "innocent" since the cost cuts come for free" (Böhringer and Rutherford, 2015, pp. 16–18, emphasis added).

Of course, modelling technical change is difficult, not least because there are competing approaches as to its appropriate representation. Sometimes technological breakthroughs do indeed seem to come about as "manna from heaven". In any case, in this instance the modellers have assumed that, because of resource efficiency inducing technical change, a range of goods and services will become considerably cheaper in 2030 than they were in 2015, resulting in higher economic growth. However, as the modelling authors make clear, this result takes no account of the costs of achieving this technical change, which may be real "hidden costs" or incurred in overcoming the barriers to increased efficiency described in Part IV - Section 2.1.

3.3.2. Macroeconometric models

Macroeconometric models have quite different theoretical foundations to CGE models. The equations describing the relationships within the model are estimated econometrically from historical data, which is not normally the case in CGE models, and they do not assume market clearing. This means that base case model outcomes tend not to be economically efficient and to have unemployed resources, meaning that policy and other interventions can improve economic efficiency and lead to increases in output and employment. This mechanism is in addition to the possible increases in output from technological change leading to reduced costs (perhaps through increased resource efficiency), which is the route through which CGE models can show increases in output, as discussed in the previous section.

A model of this kind, the E3ME model of Cambridge Econometrics, was used to inform the European Commission's work on the economic implications of increased resource productivity. The study describes its results as follows: "The scenarios in this report are based around different resource productivity [RP] targets for the EU28, ranging from a modest improvement in RP (1% pa) to ambitious improvements (3% pa). In the period to 2030 this translates to an RP improvement of around 15% for the modest scenario and 50% for the ambitious scenario. Policies to improve RP are assumed to fall under three categories: market-based instruments such as taxation, private-funded measures such as recycling and public-funded capital investment to improve efficiency. Revenues from the market-based instruments are assumed to be used to fund the investment, with the remainder used to lower labour taxes.

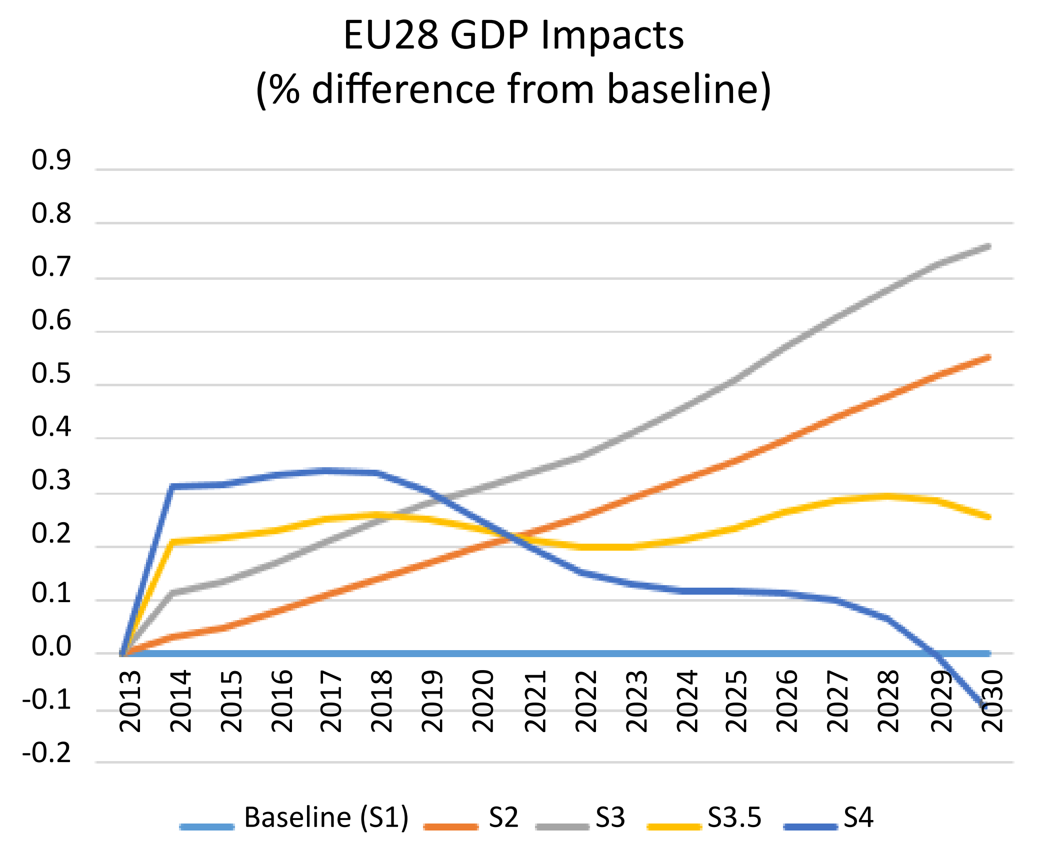
"Prior to the scenario analysis, the E3ME model was set up to provide marginal cost information for the different abatement options. The scenarios are based on the results from this analysis, expressed as a set of cost curves. It

should be noted that these cost curves are for the most part top down in nature as there is little bottom-up information on economy-wide reductions in material consumption.

"Given these assumptions, the modelling results suggest that resource productivity improvements of around 2% to 2.5% pa can be achieved with net positive impacts on EU28 GDP. This is because the benefits of higher efficiency levels outweigh the costs of making the improvements to efficiency. Beyond a rate of 2.5% pa, however, further improvements in RP are associated with net costs to GDP as the abatement options become more expensive" (CE and BioIS, 2014, pp. 5–6). These results are illustrated in Figure 46.

However, the study also makes clear that the increase in GDP is driven not so much by the increase in resource productivity as by the policy mechanism used to bring it about — an Environmental Tax Reform (ETR): "The scenario results suggest that reductions in resource consumption can be achieved with a positive impact on European GDP. This is mainly driven by our assumption for revenue recycling that the revenues generated get used to reduce income tax rates and employers' social security payments. This is the concept of 'Environmental Tax Reform (ETR)' where an environmental tax such as an emission tax is used to cut GHG emissions but revenues generated are used to simulate *[presumably this should be "stimulate" – Eds]* the

Figure 46: EU GDP impacts from increased resource productivity (RP)



Source: CE and BioIS (2014), Figure 21, p. 40.

Key: Overall RP improvement between 2014 and 2030: Baseline Scenario 1 (S1) 14%; S2 15%; S3 30%; S3.5 40%; S4 50%

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

economy at the same time" (CE and BioIS, 2014, p. 46). Earlier in the report, the mechanism is explained as follows: "We have introduced a tax on the consumption of raw materials (biomass, minerals, metals and energy where applicable). Tax revenues are collected by national governments and recycled back at Member State level through lower income taxes and employers' social security contributions (i.e. labour taxes) in order to achieve revenue neutrality" (CE and BioIS, 2014, p. 35). In a case where "there is no recycling of the revenues from MBIs [taxes]… the net positive GDP impacts are much smaller and become negative over time" (CE and BioIS, 2014, p. 6). This puts a very different light on the GDP effects of resource efficiency increases per se.

Another study, using a similar model (the global GINFORS model developed by the German consultancy GWS) looked at the economic implications of radical global resource efficiency increases in the use of energy, metals and minerals, land, water and biomass. This study was unusual in that its reference case sought to take account of the economic implications of *not* increasing resource efficiency in a world of rising population and incomes, but finite land resources. One result was very high food prices, even when substantial improvements in agricultural productivity were assumed. When resource efficiency measures were introduced into the model, it found: "The investment in new technologies for renewable energies, grids and the energy efficiency of buildings and recycling pushes the circular flow of income and thus raises growth. The long-run rise of the capital stocks means higher capital costs and insofar higher prices. This has negative effects on GDP in later years. On the other side the lower material intensity of the global economy reduces costs and prices in manufacturing and the lower demand for fossil fuels and ores in addition drops extraction prices down.

"For the global economy these impacts are clearly positive. … The deviation of global GDP … from the reference is positive and rises till 2030 and reduces then slightly reaching 5.2% in 2050. The substitution of raw materials like fossil fuels, ores and non-metallic minerals reduces costs in manufacturing and therefore gives positive impacts on GDP. The mining and quarrying sectors and the directly following stages of production suffer of course from the reduction of demand of their products, which gives negative impacts on GDP. For a country in question the GDP effect of material efficiency is depending from its position in the international division of labour. Those countries that are importing materials are winners and those that are exporting materials are losers" (Meyer et al., 2015, pp. 53–54). In this scenario, investment is shown to be 17 percent higher by 2050 than in the reference case. This extra investment is able to increase GDP, rather than crowding out other investment or reducing consumption, because of this model's availability of unemployed resources. The size of this GDP increase will be limited by the amount of these unemployed resources. Because CGE models generally do not have unemployed resources, since they are based on assumptions of market clearing, they do not show increases in GDP through this mechanism.

Investment is not the only driver for higher output from increases in resource efficiency in models of this kind. Thus Lutz and Lehr (2015, pp. 487–488) model an Ambitious (Energy) Efficiency scenario for Germany, finding that this increases German GDP 0.8 percent above the reference by 2030. However, over 70 percent of this increase derives from increased consumption due to the reduced cost of energy services. This is similar to the cause of GDP growth from resource efficiency increases in CGE models, when this is brought about by technical change.

3.3.3. System dynamics models

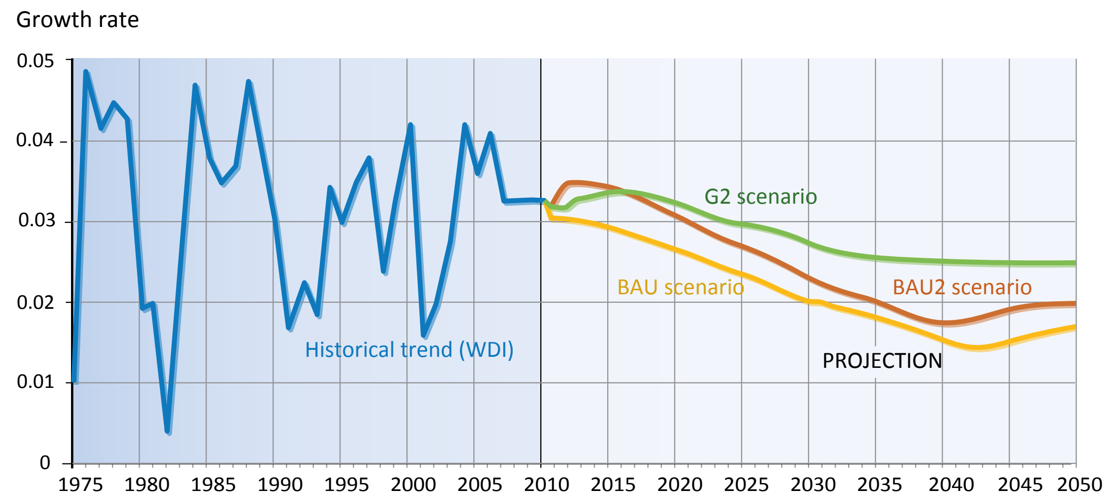
System dynamics models the relationships between different system components on the basis of causal loops that have positive or negative effects. An example of this is the Threshold 21 (T21-World) model, which was used in the UN Environment Green Economy Report (GER) (UN Environment, 2011c) to compare

Part II: Resource efficiency: trends, economics and governance

the economic outcomes of different scenarios. Figure 47 shows the historical growth rate of the world economy from 1975 to 2010, and three scenario projections from 2010 to 2050. The BAU line gives the outcome of a business-as-usual (BAU) development path, involving the continuing depletion of natural capital. As both the Green2 (G2) and BAU2 lines incorporate the same levels of higher investment than BAU, they both lie above the BAU line. However, they differ in that BAU2 has the same pattern of investment as BAU, but G2 has relatively higher investment in resource efficiency and natural capital. The growth rate of G2 exceeds that of BAU2 by about 2017, and stays above it through the projection period, such that by 2050 world GDP is 16 percent higher in G2 than in BAU2 (UN Environment, 2011c, p. 519).

The transmission mechanism to higher growth in this model differs from both CGE and macroeconometric models, and is described in the Annex to the modelling chapter in the UN Environment report (UN Environment, 2011c, pp. 537–540). There are in fact two mechanisms at work. Firstly, natural capital enters into the production functions of some of the economic sectors in the model. These are standard Cobb-Douglas production functions of the form $Y=A*K^{\alpha}*L^{(1-\alpha)}$, where Y is output, K is the produced capital stock, L is labour, A is Total Factor Productivity, and α is the output elasticity of capital. The novelty here is that natural capital is incorporated into the A term. In addition, the model directly represents several environmental dimensions (including land, water energy, waste and emissions) and these also have an influence on output: "In the GER BAU scenario the feedback effects from natural resource depletion are sufficiently important that the annual rate of world GDP growth gradually falls from about 2.7 percent per year in the period 2010–2020 to 2.2 percent in 2020–2030 and further to 1.6 percent in 2030–2050. … BAU scenarios push consumption, stimulating economic growth in the short and medium term, thus exacerbating known historical trends of depletion of natural resources. As a consequence, in the longer term, the decline of natural resources (e.g. fish stocks, forestland and fossil fuels) has a negative impact on GDP (i.e. through reduced production capacity,

Figure 47: Historical (1975–2010) and projected (2010–2050) growth rates for three scenarios



Source: UNEP (2011c), Figure 13, p. 523.

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

higher energy prices and growing emissions) and results in a lower level of employment. Additional consequences may include large-scale migration driven by resource shortages (e.g. water), faster global warming and considerable biodiversity losses.

"The green scenarios, by promoting investment in key ecosystem services and low carbon development, show slightly slower economic growth in the short to medium term, but faster and more sustainable growth in the longer term. In this respect, the green scenarios show more resilience, by lowering emissions, reducing dependence on volatile fuels and using natural resources more efficiently and sustainably" (UN Environment, 2011c, pp. 518, 519).

Figure 47 shows this dynamic quite clearly, with the rate of economic growth in the BAU scenarios falling due to natural resource depletion, and that in the G2 scenario falling less quickly, and becoming greater than the growth in the BAU2 scenario from about 2017. This provides a second unusual example of modellers seeking to capture the negative environmental and resource impacts of "business-as-usual" in the reference scenarios, thereby increasing the modelled benefits of increased resource efficiency.

3.3.4. The rebound effect

If resource efficiency leads to lower microeconomic costs and higher economic growth, as suggested by the modelling studies reviewed in the previous sections, it might be expected that some of the savings in resource use arising from increased resource efficiency will be reduced by the growth in economic activity. This phenomenon is termed the "rebound effect". One result of this effect is that actual resource savings from increases in resource efficiency tend to be less than *ex ante* engineering-based estimates of the technical potential of those measures. The rebound effect is thus measured as the percentage difference between the expected resource savings from the efficiency measures and those actually achieved.

The literature distinguishes between three types of rebound effect: direct, indirect and macroeconomic (Barker et al., 2007). In each case, the rebound effect occurs because an increase in resource efficiency has reduced the cost of a good or service, freeing up income and thereby increasing effective demand. The direct rebound effect occurs when more efficient delivery of a good or service results in an increase in demand for that good or service (e.g. when people spend cash savings from increased vehicle fuel efficiency on driving more). The indirect rebound effect occurs when more efficient delivery of a good or service results in an increase in demand for another good or service that uses the same resource (e.g. a hotel that installs water-efficient bathroom fittings, and then invests the cash savings in a water-intensive swimming pool). The macroeconomic rebound effect is the result of all the direct and indirect rebound effects interacting throughout the economy. In each case, the physical resource saving is less than might have been expected from calculations of the efficiency potential.

The now extensive literature on the nature and size of the rebound effect (see Herring and Sorrell (2009) for a review) is outside the scope of this report, but the evidence suggests that rebound effects may be significant. For example, Allan et al. (2009, Table 4.2, p. 85) found the macroeconomic rebound effect from a 5 percent increase in industrial energy efficiency to be 36 percent and 14 percent for electricity, and 55 percent and 31 percent for non-electricity, in the short and long term respectively. Macroeconomic modelling of increased resource efficiency, such as that discussed earlier in this chapter, includes rebound effects.

Rebound effects can actually result in increases in resource efficiency leading to an overall *increase* in resource use (the so-called Jevons Paradox), although this is relatively rare. On the other hand, policy measures can mitigate rebound effects (Herring and Sorrell, 2009, p. 241), most obviously by increasing the cost of the resource that has been the subject of the efficiency measure (for example, through resource or environmental taxation). Such measures will be required where the objective of resource efficiency improvements is actually to reduce the quantity of the resource used or its associated environmental impacts by a given amount (for example, if increases in energy efficiency are intended to aid the attainment of fixed carbon-reduction targets). In the example using the GINFORS model cited in Part II - Section 3.3.2, in which resource efficiency increases were stimulated through increases in resource taxation, the tax revenues had to be recycled by reducing firms' production taxes. This was due to the rebound effects of the usual mechanism of reducing firms' social security contributions being too strong for the resource-saving targets to be reached (Meyer et al., 2015, p. 43).

3.3.5. Resource efficiency and employment

If increased resource efficiency leads to increased output (as in the studies reported in the previous sections), then other things being equal, it might be expected that it would also lead to increased employment. This is found to be the case in a study by the Club of Rome, which uses an input-output model to explore the effects of considerable increases in material and energy efficiency, and in renewable energy. The study reports its results thus: "This means that unemployment rates — compared to today — could be cut by a third in Sweden and the Netherlands, and possibly more, maybe even cutting unemployment in half — provided that some of the likely trade surplus gains would be used for investments domestically. In Spain the unemployment rate is likely to be reduced from the current over 20% to somewhere close to 15%, in Finland unemployment would be cut by a third, and in France by almost a third, provided that some of the likely trade surplus gains would be used for investments domestically" (Wijkman and Skånberg, 2015, p. 39). The mechanism of employment increase here is clearly investment of the trade surplus that arises from importing fewer fossil fuels and materials. Of course, this means that the countries exporting fossil fuels and materials will experience reduced income and employment.

In addition, the input-output model used is unable to capture all of an economy's supply-demand interactions. As the authors acknowledge, "It would of course have been preferable to having *[presumably this should be "have" — Eds]* had …more economic dynamics, like in a Computable General Equilibrium (CGE) and/or econometric model, to grasp how changes in relative prices are likely to influence both supply and demand" (Wijkman and Skånberg, 2015, p. 56). Similarly to when estimating macroeconomic impacts from changes in microeconomic costs arising from resource efficiency, it is necessary to use fully specified macroeconomic models to simulate the full extent of employment changes throughout the economy from increases in resource efficiency. This is because jobs may be gained in some sectors but lost in others. Poschen (2015, p. 35) from the International Labour Office (ILO) is careful to draw the distinction between gross and net effects on employment from moves to a "green" economy. He also offers some evidence that "green", including more resource-efficient, sectors have higher employment elasticities of demand than the economic average. Expansion of these sectors will thus lead to relatively higher employment (Poschen, 2015, pp. 33–34).

In macroeconomic models, changes in employment arise not only from the relation between output and employment, but also from the way the labour market is modelled and, most importantly of all, whether the models contain involuntary unemployment (many CGE models assume that labour markets always clear). In the CGE modelling exercises reported above, neither the IEA (2012b) modelling of their Efficient World Scenario, nor the Böhringer and Rutherford modelling of the EMF (2015) circular economy report employment changes from the resource efficiency increases. This suggests that these are not significant outputs from the models employed.

Macroeconometric models, with their unemployed resources, offer more scope for changes in employment resulting from resource efficiency increases. For example, in its S3 scenario the CE and BioIS (2014) study reports a 1 percent increase in EU employment (about 2 million net extra jobs) above the baseline by 2030. However, as with the GDP increases in this study, as reported above, these employment effects are also largely the result of using the revenues from resource taxes to reduce labour costs. Poschen (2015, p. 39) cites an ILO/IILS (International Institute for Labour Studies) study that suggests that "up to 14 million net new jobs could be created if a tax on CO_2 emissions were imposed and the resulting revenues were used to cut labour taxes". The employment gains for the EU from resource efficiency in the scenario using the GINFORS model discussed in Part II - Section 3.3.2 are similar, falling from 2 percent in 2030 to just under 1 percent by 2050.

Similar to macroeconometric models, the T21-World model does not assume full employment. In the G2 scenario, employment is 0.6 percent (21 million) lower in 2020 than in BAU2, but 28 million higher by 2050.

3.4. Conclusions

Increasing resource efficiency can substantially reduce resource-related costs to firms and households, and associated environmental impacts. When these resource efficiency increases come about through pure market processes, it is clear that resource efficiency and economic efficiency are aligned, and will result in economic growth. Indeed, increased economic efficiency is one of the principal drivers of economic growth.

When resource efficiency does not come about through pure market processes, the economic implications of increasing it, perhaps through public policy, are less clear. In this case, there are market failures or other barriers to resource efficiency, as discussed above. If there are externalities, and these are appropriately internalized through public policy, economic efficiency and human well-being will increase. Whether monetary economic output (GDP) does so too will depend on the externality and the policy measure used to internalize it.

Where the wedge between resource efficiency and economic efficiency arises from other causes, such as the barriers discussed in Part II - Section 3.1, the GDP implications of measures to increase resource efficiency are uncertain. Removing these barriers may involve costs, which may be high enough to offset the cost benefits of increased resource efficiency. In such cases, increasing resource efficiency will not result in increased economic efficiency and net economic benefits.

Estimating the macroeconomic benefits of increasing resource efficiency requires macroeconomic models, such as those reviewed briefly in Part II - Section 3.3. As discussed, these models use different assumptions and mechanisms to model increases in resource efficiency. These include the cost reductions resulting from increased resource efficiency, the associated technical change, the increased investment needed to achieve it, and the impacts on productivity to which these investments, when they are in natural capital, may lead.

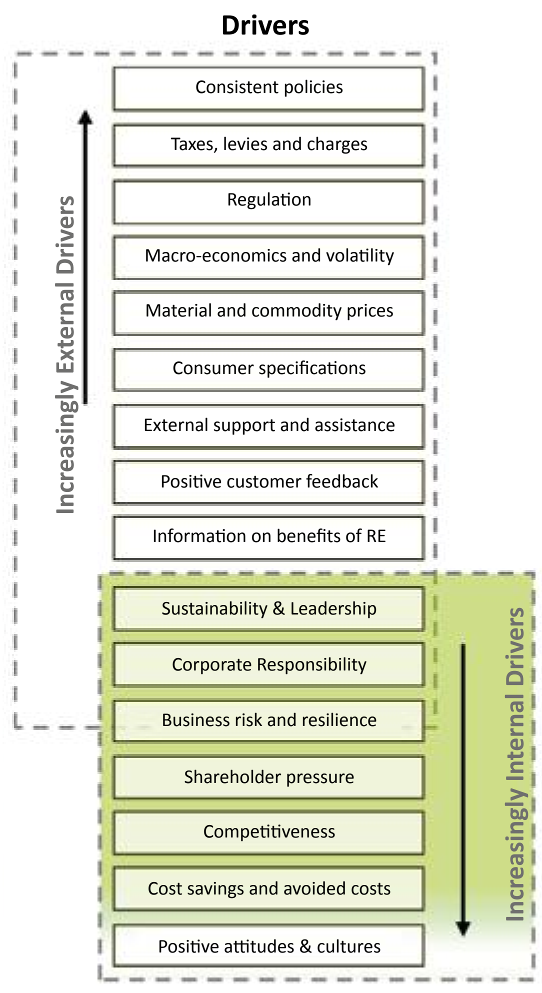
Whether increased resource efficiency will lead to increased employment in these models also depends on the nature of the macroeconomic modelling being employed. Assumptions about unemployed resources, and the way the labour market is modelled, are especially important.

Most attempts to model the economic implications of increased resource efficiency, where this is not driven by markets, are able to take account of the costs of removing the barriers to resource efficiency to only a very limited extent or not at all. Nor do many models capture the costs of transition (for example, retraining costs and costs of migration). Modelling results in these cases effectively shows the macroeconomic benefits of increasing resource efficiency if the barriers to such an increase could be removed without incurring costs. Some models similarly assume that the technical change leading to increased resource efficiency is achieved, or that resource efficiency policies are implemented, at no or very little cost. There may, however, be significant costs in removing barriers to increased resource efficiency, transitional costs in achieving it, costs involved in stimulating the requisite technical change, or policy may be implemented inefficiently. In these cases, the macroeconomic benefits from increased resource efficiency would be reduced and there could even be net costs from such changes.

On the other hand, the baseline scenarios of some modelling results do not take into account the avoided resource disruptions and environmental damage — which provide the rationale for resource efficiency measures in the first place. In such cases, the model results underestimate (perhaps very significantly) the benefits of resource efficiency. In addition, the macroeconomic costs of technical change through research and development (R&D) and stimulating innovation may be quite low, and approximate the "manna from heaven" assumptions in some models. Moreover, there is persuasive microeconomic evidence of substantial potential benefits to be gained from resource efficiency. This should encourage policymakers to introduce policies that will overcome the barriers to increased resource efficiency at low or no cost, so that all or nearly all of the available benefits from resource efficiency suggested by both the microeconomic estimates and the macroeconomic models are realized. Figure 48, the antidote to Figure 42 which shows the barriers to resource efficiency in businesses, shows some of the internal and external drivers through which they may be addressed.

It is striking that, as shown in this chapter, different types of macroeconomic models with different structures and underlying assumptions suggest that resource efficiency measures could perhaps have very substantial macroeconomic gains. Although the modelling studies cited above differ in the size of their estimates, all of them show that increasing resource efficiency can result in higher economic growth and/or employment, for most of them even when environmental benefits are not taken into account. However, it is important that policymakers seeking these benefits in practice are aware of the actual economic processes that have brought them about, so that they can introduce policies that are likely to have these effects. The models do not suggest that markets will achieve these higher levels of resource efficiency on their own. Rather, that higher

Figure 48: Drivers to stimulate businesses to become more resource efficient



Source: AMEC and BioIS (2013), Figure B9, p. 83.

growth and employment arising from greater resource efficiency are the result of higher rates and different types of innovation and technical change than those driven just by markets. They may be the outcome of higher investments in resource-efficient infrastructure and products, and intelligent, targeted regulation. They can also arise from environmental tax reform that changes the balance between the costs of labour and materials by shifting the base of taxation away from the former towards the latter and towards pollution. This increases the economic return to resource-efficient and less environmentally damaging products and processes.

It is therefore right to be both cautious about the actual numbers in the results of studies on the macroeconomic outcomes from increased resource efficiency, but also optimistic that, if resource efficiency increases are achieved through efficient policy, there will be benefits in terms of both increased output and increased employment. This is also a message that applies to the economic output from the new CGE modelling that has been carried out for this report (see Part IV - Chapter 2).

While the distributional implications of increased resource efficiency are largely beyond the scope of this report, the GINFORS modelling results reported above and in Part IV - Chapter 2 show that these implications can be serious, especially between resource-exporting and resource-importing countries. They will assuredly need to be addressed in any policy strategy to enhance resource efficiency globally. In fact, such a strategy provides an opportunity to bring together three key economic resource-related issues: international efforts to address resource price volatility, environmental tax reform, and revenue recycling. Addressing these three issues in a coordinated manner for the benefit of both resource-importing and resource-exporting countries is a resource-governance challenge for the international community in the decades ahead. The aim is for increased resource efficiency to promote the sustainable development of resource-exporting countries as well as net-resource importers.

It is to broader issues of resource governance that this report now turns.

4. GLOBAL GOVERNANCE OF RESOURCES AND IMPLICATIONS FOR RESOURCE EFFICIENCY

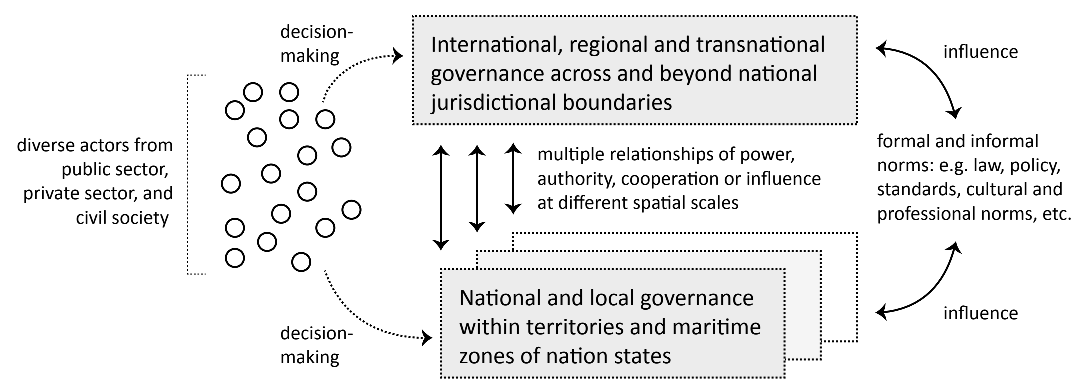
4.1. Introduction

All decision-making is shaped by, and embedded within, a complex global web of relationships between individuals and institutions. *Global governance* refers to the many ways in which individuals and institutions, public and private, manage their common affairs in this context (CGG, 1995, Dingwerth and Pattberg, 2006, Weiss and Thakur, 2010, Donahue and Nye Jr., 2000). Global governance *of resources* is a process characterized by a wide variety of actors, normative frameworks, hierarchical relationships, and associated spatial boundaries (Young, 1997, Speth and Haas, 2009, Biermann and Pattberg, 2008). These components are summarized below and illustrated in Figure 49.

Actors – The actors that participate in global resource governance include but are not limited to governments, intergovernmental organizations (IGOs), private entities from commercial and non-profit sectors, and diverse communities within civil society (Biermann and Pattberg, 2008, EEA, 2011b, Levy and Newell, 2004). Each of these actors pursues different sets of interests at different spatial scales, in different social, cultural, political, economic and environmental contexts (Harris, 2016).

Normative frameworks – Decision-making by different actors concerning resources is enabled, constrained and influenced by a wide variety of normative frameworks (Bodansky et al., 2007, Pattberg, 2005, Young et al., 2008). More formal normative frameworks include treaties, laws, regulations, policies, contractual agreements and technical standards (Hunter et al., 2015, Morrison

Figure 49: Key components of global resource governance



Source: Authors.

and Roht-Arriaza, 2007). Less formal normative frameworks include administrative, commercial, professional, cultural and interpersonal practices.

Behavioural relationships – Both actors and normative frameworks are influenced and shaped by relationships of power, authority, cooperation or influence at multiple levels (Newig and Fritsch, 2009, Bache and Flinders, 2004, Weibust and Meadowcroft, 2014). These relationships are often described as *vertical* when they are predominantly hierarchical, *horizontal* when they are predominantly cooperative and voluntary.

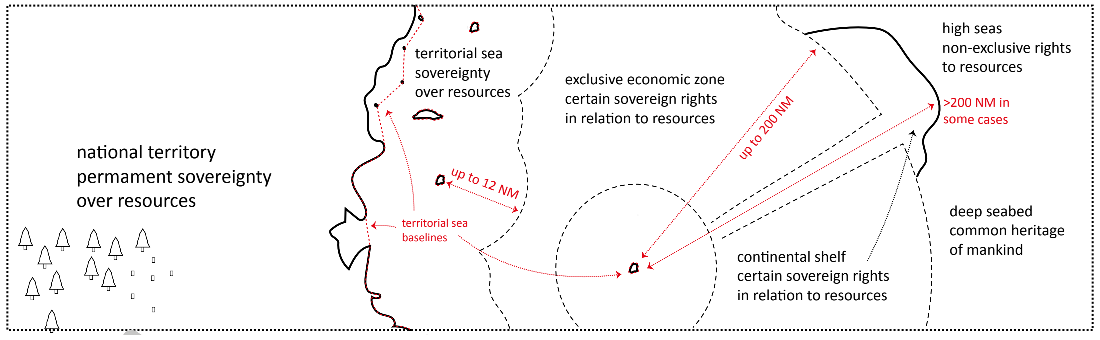
Spatial boundaries – Different actors and normative frameworks shape global resource governance at different spatial scales, including local, national, regional and international. As explained in more detail below, the spatial boundaries of governance at each of these scales is often not aligned with the biophysical and spatial characteristics of resources. Many resources straddle, migrate across, or are affected biophysically by activity located beyond jurisdictional boundaries (Benvenisti, 2002, Kliot et al., 2001). Many resources are also moved across jurisdictional boundaries, through various interconnected and globalized supply and value chains (WTO, 2014, OECD et al., 2014). The participation of entities other than national governments (e.g. corporations) in decision-making about resources that transcends national jurisdictional boundaries is commonly described as *transnational* in character (Betsill and Bulkeley, 2004).

Using the components outlined above as an analytical template, this chapter identifies the key features of global resource governance, highlighting their significance in both enabling and constraining different actors' efforts to use resources more efficiently. The chapter also identifies several promising ways in which global resource governance is beginning to respond to the urgent need to improve resource efficiency. This includes through the protection and definition of resource-related rights; coordinated management of resources and resource-related impacts across sectors, boundaries and globalized value chains; and recognition of the multiple public and private benefits of resources. These responses are apparent at local, national, regional and global scales, in both developed and developing countries.

4.2. Key features of global resource governance

International law establishes a basic architecture of global resource governance by recognizing

Figure 50: The basic architecture of global resource governance



Source: UNEP (2011c), Source: Authors, adapted from Geoscience Australia (2017).

several general rights and obligations of nation states. These are summarized below and illustrated in Figure 50.

Resources on land – are subject to the permanent sovereignty of nation states within their respective territories (UNGA, 1962, Schrijver, 1997). The Convention on Biological Diversity (CBD, 1992) recognizes that "States have, in accordance with the Charter of the United Nations and the principles of international law, the sovereign right to exploit their own resources pursuant to their own environmental policies, and the responsibility to ensure that activities within their jurisdiction or control do not cause damage to the environment of other States or of areas beyond the limits of national jurisdiction." The above principles divide rights and responsibilities concerning resource governance into exclusive and spatially discrete national units, except in the several locations (e.g. Antarctica) where multiple states currently assert overlapping claims to territorial sovereignty (CIA, 2016, Huth, 1998).

Marine resources in zones of national jurisdiction – The United Nations Convention on the Law of the Sea (UNCLOS, 1982) recognizes the sovereignty of coastal states over a territorial sea extending up to 12 nautical miles (NM) from baselines determined in accordance with the Convention, and over archipelagic waters claimed by certain archipelagic states. It also recognizes certain exclusive sovereign rights and obligations of coastal states concerning resources located on their continental shelf, or in an exclusive economic zone (EEZ) extending up to 200NM from relevant baselines. Many oceans and seas currently feature, and are characterized by, overlapping claims to sovereignty or exclusive sovereign rights concerning resources (Milligan, 2012). Furthermore, less than half of the world's potential international maritime boundaries have been delimited (Prescott and Schofield, 2004, Schofield, 2011).

Marine resources located beyond zones of national jurisdiction – UNCLOS and associated agreements also recognize rights and obligations of states concerning resources located on the high seas and deep seabed (Warner, 2009). Resources in these zones (e.g. fisheries, poly-metallic nodules, genetic resources) are not subject to the sovereignty or sovereign rights of states, and are managed through cooperative frameworks including the International Seabed Authority, International Whaling Commission, and regional fisheries management organizations (RFMOs). Resources on the deep seabed are recognized as forming part of the "common heritage of mankind" (Baslar, 1998).

Key features of global resource governance that have been established within this basic architecture are summarized below, at national (including local), regional and international (including transnational) scales. Their important implications for resource efficiency are then discussed in Part II - Section 4.3.

4.2.1. National resource governance

Within the territories and maritime zones of nation states, the actors participating in resource governance include government institutions, commercial and non-profit entities from the private sector (including subsets of transnational entities), and communities of interest within civil society. The behaviour of these actors influences, and is influenced by, national laws, policies, customs and other norms, which all vary considerably from country to country. Common formal normative features of resource governance at a national scale include the following:

Roles, responsibilities and organization of government – National laws and constitutions generally define the major roles and responsibilities of government in relation to resources, and allocate these to different government institutions including parliaments, executive agencies, and the judiciary. Government institutions are commonly established at multiple nested levels of scale, with certain responsibilities allocated to regional or local governments. In countries that are organized federally (e.g. Australia, Brazil, Canada, Germany, India, Mexico and the United States), resource responsibilities are divided between the national government and partially self-governing subnational territories. The resource responsibilities of executive governments are also commonly divided along sectoral lines, e.g. through the creation of separate ministries responsible for energy, mining, forestry, fisheries, agriculture, water resources, and/or environmental management.

Management and development of resources – Government agencies in many countries have established detailed policy frameworks concerning the management and development of their resources and the allocation of associated benefits. Conventionally, these are focused on particular sectors (e.g. extractive industries, agriculture, water, fisheries and aquaculture), with limited cross-sectoral integration. In recent decades, national policy frameworks concerning resources have increasingly focused on various important crosscutting issues, including: livelihoods, poverty and human rights (Young and Goldman, 2015, IFAD, 2011, Zillman et al., 2002, Toulmin and Quan, 2000, Ellis and Biggs, 2001); spatial and development planning (IPCC, 2014a, IPCC, 2014b, UN-Habitat, 2009, CBD and GEF, 2012); ecosystem-based management (UN Environment, 2011e); climate change mitigation and adaptation (IPCC, 2014a, IPCC, 2014b, Lim and Spanger-Siegfried, 2004); the resource nexus (Kurian and Ardakanian, 2015, UN-ESCAP, 2013); the green economy (OECD, 2012a, OECD et al., 2012, UNDESA, 2012); resource efficiency (UN Environment, 2014b, EC, 2011d); and sustainable development (UNDESA, 2015). Noteworthy examples relating specifically to resource efficiency are discussed further in Part II - Section 4.3.

Rights concerning resources – National legal systems recognize a wide variety of exclusive or non-exclusive rights (and corresponding obligations) concerning resources, including property rights (Hanna et al., 1996, McHarg et al., 2010, Barnes, 2009, Aggarwal and Elbow, 2006). Key property rights that are recognized in each country in different bundled groups include: withdrawal (right to obtain products of a resource); management (right to regulate internal use patterns and transform the resource by making improvements); alteration (right to change the set of goods and services provided by a resource); exclusion (right to determine who will have an access right, and how that right may be transferred); and alienation (right to sell or lease some or all rights) (Schlager and Ostrom, 1992).

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

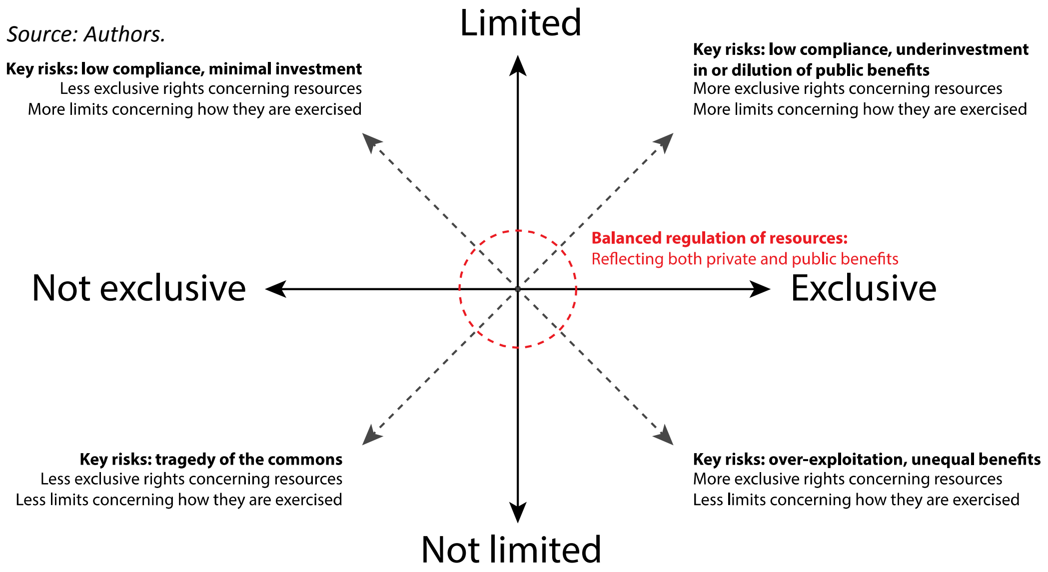
Limitations concerning resources – National legal systems also place a wide variety of limitations on how rights concerning resources are exercised in different circumstances. Interactions with natural resources are, for example, limited by: spatial and development planning; prior authorization requirements for the use and development of resources; reservation of resources for future use or strategic reasons; protected areas and other forms of spatial management (Dudley, 2008, Stolton et al., 2013); restrictions on certain interactions with protected species, habitats and ecosystems (Bowman et al., 2010); control measures concerning pollution; and procedural obligations, including strategic and project-level environmental impact assessments (Craik, 2011). Generally, such restrictions aim to maintain or enhance the public benefits of resources (e.g. drinking water supply, taxation income from resource rents) or the aggregate level of private benefits (e.g. through unitization of petroleum deposits, or coordinated management of agricultural irrigation).

The interaction of relevant rights, and limitations concerning how these are exercised, shape societal expectations concerning resources and the allocation of resource-related benefits to support different public or private interests. Figure 51 maps, in basic terms, the variation of resource-related rights on two dimensions (degree of exclusivity, and limitation on how rights are exercised) across different national legal systems and key associated policy risks. These risks include low compliance with formally defined rights and limitations; underinvestment in resource management, including for resource efficiency; exploitation of resources at unsustainable levels; and inequitable allocation of benefits from resources.

An important issue in several countries is the discrepancy between formally recognized rights to resources, and the resource-related expectations and dependencies of local communities (Toulmin and Quan, 2000). Many local communities around the world are highly dependent on resources (e.g. forests, fisheries, agricultural land) over which they do not enjoy formal property rights (Suárez et al., 2009, Palmer, 2012, RRI, 2015). In some cases, economic development policies

Figure 51: Variation of rights on two dimensions and key policy risks concerning resources

Source: Authors.



Part II: Resource efficiency: trends, economics and governance

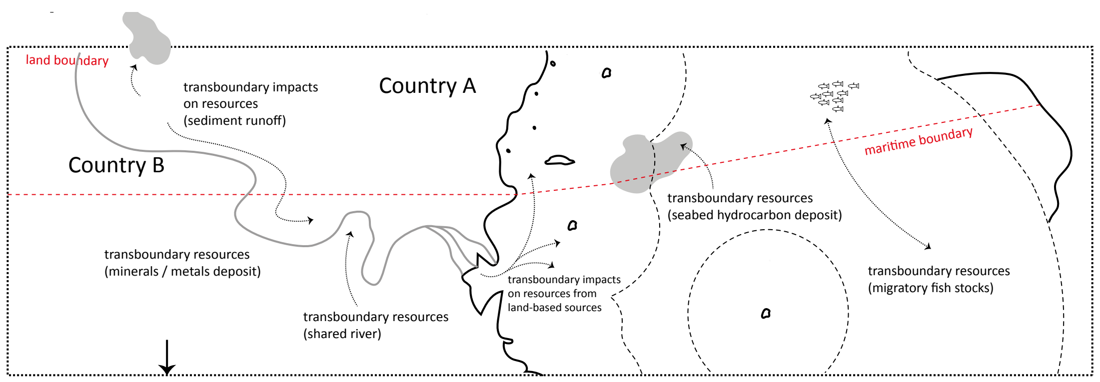
in several low- and middle-income countries have allowed commercial sector actors to acquire formal property rights on a large scale, including to enable mining and plantation agriculture (Cotula et al., 2009, Cotula et al., 2014). These acquisitions are often characterized by the involvement of transnational corporations (TNCs), including state-owned enterprises from other countries (Cotula, 2013, Holden and Pagel, 2013, UNCTAD, 2009). TNCs comprise national entities located in more than one country, linked by ownership or otherwise, under a coherent system of decision-making in which they can exercise significant influence over each other and share knowledge, resources and responsibilities (Weissbrodt and Kruger, 2003, Sauvant, 2015).

Negative outcomes associated with large-scale property acquisition in low- and middle-income countries include: expropriation without adequate compensation of formal rights held by individuals and communities; extinguishment of long-standing informal rights held by individuals and communities; dislocation of local communities from acquired areas; destruction of local livelihoods; and resource development that maximizes marketable private benefits (e.g. timber extraction) to the detriment of public benefits (e.g. access to clean water) (Anseeuw et al., 2012). Promising initiatives designed to address these challenges are summarized in Part II - Section 3.3.

In many contexts the spatial scale of resources, and impacts of economic activity on resources, transcend national boundaries. For example, approximately 40 percent of the world's population lives in river and lake basins comprising two or more countries (UN-Water, 2008), and many living resources (e.g. fish stocks) migrate across national boundaries. Key biophysical spatial interactions between resources and national boundaries are illustrated in Figure 52.

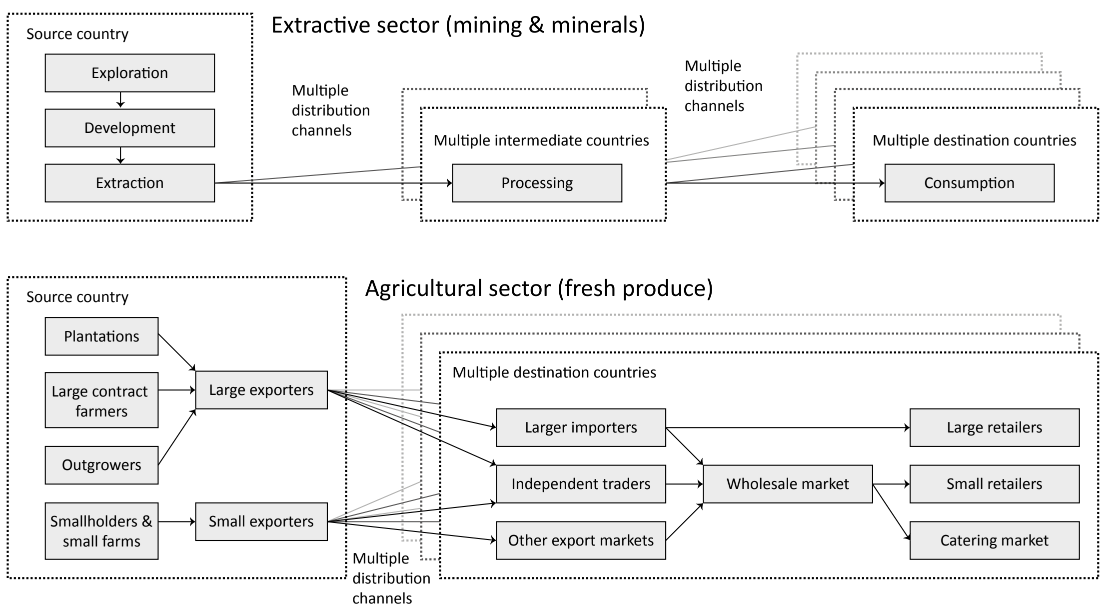
The movement of resources across national boundaries is also driven by the increasing organization of production, trade and investment into globalized supply and value chains (OECD et al., 2014, Kaplinsky and Morris, 2001). These chains have diverse characteristics — including different degrees of complexity, fragmentation, interconnectedness, and resource intensity, and different structures of control and ownership (OECD, 2013a). Figure 53 provides simplified examples of supply and value chains in the extractive sector (adapted from Dicken (2011)) and agricultural sector (adapted from Dolan and Humphrey (2000) and Dicken (2011)). These examples are illustrative of how many supply and value chains for resources

Figure 52: Key biophysical interactions between resources and national boundaries



Source: Authors.

Figure 53: Illustrative structures of global supply and value chains for resources



Source: Authors, adapted from Dolan and Humphrey (2000) and Dicken (2011).

are characterized by interactions between multiple actors across multiple countries.

Efficient use of resources across national boundaries and globalized value chains depends on cooperation between relevant actors at regional and international scales. Sections 4.2.2 and 4.2.3 in Part II provide a broad overview of the actors that participate in resource governance at these scales, and key normative frameworks that have been established with a view to coordinating their activities.

4.2.2. Regional resource governance

The actors participating in resource governance at a regional level include national governments, regionally and internationally focused IGOs, private transnational entities operating on a commercial or non-profit basis, and regional communities of interest within civil society. Key coordination frameworks involving different combinations of these actors include the following:

Management of resources and the environment – Regional inter-State agreements in this field have proliferated in recent decades, focusing on management of: shared rivers and water resources (Benvenisti, 2002, Kliot et al., 2001); marine resources, particularly fisheries (Russell and Vanderzwaag, 2010); marine and terrestrial transboundary pollution (Birnie et al., 2009, Hunter et al., 2015); transboundary hydrocarbon resources, including those subject to competing jurisdictional claims (Bastida et al., 2007, Weaver and Asmus, 2006); migratory species (Birnie et al., 2009, Hunter et al., 2015); and biodiversity conservation, including by establishing transboundary protected areas (Sandwith et al., 2001). Several of these agreements have established specialized institutions for regional resource governance, e.g. the South Pacific Regional Environment Programme, and OSPAR Commission for

protecting the North-East Atlantic and its resources. Regional cooperation concerning resources and environmental management is also funded and brokered by several multilateral institutions, notably the United Nations Environment Programme (UN Environment) and the Global Environment Facility (GEF). Under the Antarctic Treaty System, several countries have agreed to collaborate in managing the Antarctic continent and its surrounding waters (Rothwell, 1996, Rose and Milligan, 2009).

Political and economic integration – Resource governance on every continent is influenced by agreements and institutions designed to foster regional economic integration. Key agreements and institutions include the: Andean Community of Nations; Association of Southeast Asian Nations; Caribbean Community and Common Market; EU; North American Free Trade Agreement; Pacific Islands Forum; South Asian Association for Regional Cooperation; and Southern Common Market in Latin America. In the case of the EU, economic integration is accompanied by political and policy integration, including detailed legal and policy frameworks designed to improve resource efficiency (see Part II - Section 4.3.2).

Development finance – Resource governance is also influenced by the activities of regionally focused development banks, including the: African Development Bank (AfDB); Asian Development Bank (ADB); Development Bank of Latin America (CAF); European Bank for Reconstruction and Development (EBRD); Inter-American Development Bank (IDB); and Islamic Development Bank. These multilateral institutions provide considerable financial and technical support to national and regional projects concerning resource efficiency. Examples include the AfDB Green Growth Framework (AfDB, 2014); ADB Clean Energy Financing Partnership Facility and contributions to the G8 3R Initiative on Waste Management (see Part II - Section 4.3.2) (ADB, 2008, ADB, 2015) ; EBRD Sustainable Resource Initiative (EBRD, 2014); and IDB Energy Sector Framework (IDB, 2015).

4.2.3. International resource governance

The key actors participating in resource governance at the international level include national governments, private (i.e. non-government) transnational entities operating on a commercial or non-profit basis, and transnational communities of interest within civil society. Many national governments' activities relating to international resource governance are undertaken in institutionalized contexts, including under the auspices of the following IGOs: Principal Organs of the United Nations; UN Environment; the United Nations Development Programme; the Food and Agricultural Organization of the United Nations (FAO); the United Nations Industrial Development Organization (UNIDO); the Organisation for Economic Cooperation and Development (OECD); the International Labour Organization; the World Trade Organization (WTO); the International Maritime Organization; the International Seabed Authority; the World Bank Group; and the GEF. A number of national governments also engage in international investment and commercial activity relating to resources via state-owned enterprises (Kowalski et al., 2013, UNCTAD, 2014).

The increasingly prominent and influential role of private transnational entities — including transnational corporations (TNCs), *not-for-profit* organizations, and other formalized partnerships and associations — has been a defining feature of international resource governance in recent decades (Braithwaite and Drahos, 2000, Pattberg, 2007, EEA, 2011b). This governance is influenced by TNCs operating in and across all sectors of the economy. In 2009, the activities of an estimated 82,000 TNCs with 810,000 foreign affiliates accounted for about a third of the value of total world exports of goods and services (UNCTAD, 2009).

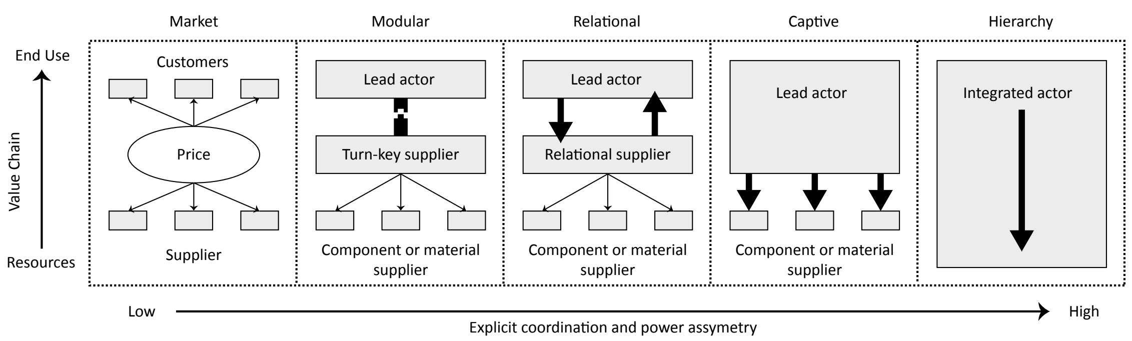
The ability of TNCs to influence resource-related decision-making across globalized value chains depends on the governance structure of the chain in question. Figure 54 presents five illustrative modes of interaction between different private sector actors within globalized value chains, and corresponding degrees of power asymmetry and coordination (adapted from Gereffi et al., (2005)). “Market” value chains involve arms-length transactions between suppliers and customers. Coordination and information exchange between these actors is limited, and switching costs are low for both. In “modular” value chains, suppliers typically produce products according to a lead actor’s specifications. Switching costs remain low due to production being coordinated by intermediate “turnkey” suppliers, and technical standardization. On the other hand, “relational” value chains involve complex non-codified interactions between the lead actor and suppliers, and are characterized by mutual dependence, high levels of asset specificity, and higher switching costs for both actors. In “captive” value chains, small suppliers’ transactions are dependent on lead buyers and they face significant switching costs. Lastly, “hierarchy” value chains are characterized by vertical integration, with governance of subsidiaries and affiliates based on headquarters’ managerial control (Dicken, 2011).

A growing number of TNCs participate in collaborative networks designed to promote sustainable business within and across global value chains. Key focal points of collaboration concerning resource efficiency include the World Business Council for Sustainable Development (WBCSD); the International Council for Mining and Metals; the Global Alliance for Banking on Values; and the Natural Capital Coalition.

Transnational not-for-profit organizations also influence international resource governance in a wide variety of capacities, including by: organizing political and educational campaigns designed to influence normative frameworks; providing financial and technical support to resource-management activities; acquiring property rights to resources; directly managing resources in partnership with relevant stakeholders; and convening dialogue between relevant stakeholders. Several not-for-profit organizations have truly global influence and reach (Spar and La Mure, 2003, Ahmed and Potter, 2006). For example, the membership of the International Union for Conservation of Nature (IUCN) includes 1000+ non-governmental organizations, 80+ nation states, 120+ individual government agencies, and 11,000+ individual scientific experts from 185 countries (IUCN, 2014).

Contemporary international resource governance is also defined by the increasingly prominent and influential role of transnational communities of interest within civil society. This is characterized by the participation

Figure 54: Illustrative modes of governance within global value chains for resources



Source: Authors, adapted from Gereffi et al. (2005).

of decentralized and fluid combinations of individuals and organizations (Ghaus-Pasha, 2005, Gemmill and Bamidele-Izu, 2002), facilitated by the dramatic increase in global Internet penetration and usage in recent years. With the global number of Internet users rising by more than 830 percent since 2000, and by more than 7,200 percent in Africa over the same period (ITU, 2015), Internet connectivity and social media have provided unprecedented opportunities for individuals, communities and organizations to act collectively at transnational scales. Key examples of transnational collective action relevant to resources include 350.org — a global network of campaigns for action to address climate change — and its fossil fuel divestment movement. As of December 2015, this had identified more than 500 institutions representing over US$3.4 trillion in assets that had made some form of divestment commitment (350.org., 2015).

The activities of the actors summarized above influence, and are influenced by, a complex network of normative frameworks relevant to resource governance. Key examples of formal frameworks are summarized below:

The 2030 Agenda for Sustainable Development – was adopted on 27 September 2015 by the 193 Member States of the United Nations (UN, 2015b). The Agenda features 17 SDGs and 169 associated targets, which United Nations Member States have committed to implement by 2030. An important feature of the 2030 Agenda is its clear recognition that social and economic development depends on sustainable management of the natural environment and its resources. Concerning resource efficiency, the Agenda establishes targets relating to: increasing water efficiency (Targets 6.4); expanding international cooperation and capacity-building support concerning water efficiency (6.a); doubling the global rate of improvement in energy efficiency by 2030 (7.3); enhancing international cooperation concerning energy efficiency research and technology (7.a.); progressive improvement of global resource efficiency in consumption and production, and decoupling of economic growth from environmental degradation in accordance with the 10-Year Framework of Programmes on Sustainable Consumption and Production (10YFP) (8.4); upgrading infrastructure and retrofitting industries, with a view to increasing resource-use efficiency (9.4); and substantially increasing the number of cities and human settlements adopting and implementing integrated policies and plans towards resource efficiency (11.b). These issues are discussed in more detail in the context of Sustainable Consumption and Production (SCP) in Part III - Chapter 1.

Multilateral agreements concerning the environment – have proliferated in recent decades in a decentralized and ad hoc manner, responding to a wide range of specific environmental challenges (Kim, 2013, Hunter et al., 2015). The collective body of more than 700 multilateral environmental agreements (MEAs) is commonly described as a partial or “fragmented” response to challenges (e.g. resource efficiency) that are cross-sectoral or systemic in nature (Biermann et al., 2009, Kim, 2013). MEAs that touch on resource efficiency issues as a subcomponent of other subject matter include the United Nations Framework Convention on Climate Change (UNFCCC) and its related instruments, including the 2015 Paris Agreement; the Convention on Biological Diversity and associated Aichi Biodiversity Targets; the Ramsar Convention on Wetlands; FAO instruments concerning agriculture and fisheries; the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal; the Rotterdam Convention on the Prior Informed Consent Procedure for Certain Hazardous Chemicals and Pesticides in International Trade; the Stockholm Convention on Persistent Organic Pollutants; UNCLOS and the supplementary United Nations Fish Stocks Agreement; and the Vienna Convention for the Protection of the Ozone Layer.

Multilateral agreements concerning trade and development – Key agreements include the

General Agreement on Tariffs and Trade, the Agreement on Technical Barriers to Trade, and other agreements concluded under the auspices of the WTO; and the Cotonou Partnership Agreement between the EU and Africa, the Caribbean and the Pacific Group of States. Trade liberalization is a core objective of the WTO agreements, with a view to achieving more efficient use of the world's resources in accordance with the objective of sustainable development (WTO, 1994, WTO, 2015). Relevant objectives referred to in the Cotonou Agreement include: promotion of institutional reforms and development for efficient market economies (article 20.d); preservation of the natural resource base (20.e); efficient maritime transport services in a safe and clean marine environment (42.1); and efficient exploitation of marine resources (84.c).

Multilateral agreements concerning human rights – These agreements establish various rights, obligations and dispute settlement mechanisms that affect governments' decision-making about resources (Bankes, 2010, Miranda, 2012). Relevant agreements include the International Covenant on Civil and Political Rights; the International Covenant on Economic, Social and Cultural Rights; the United Nations Declaration on the Rights of Indigenous Peoples; and the Aarhus Convention on Access to Information, Public Participation in Decision-Making and Access to Justice in Environmental Matters. These and similar agreements recognize and protect certain individual and community rights — relating generally to access and control of certain resources, and informed participation in resource-related decision-making (Zillman et al., 2002).

Bilateral or multilateral agreements concerning foreign investment – More than 3,000 inter-State agreements relating to international investment have been concluded to date (UNCTAD, 2015). The general purpose of these international investment agreements (IIAs) is to ensure that States parties adhere to certain standards of treatment of foreign investors or investments (Salacuse, 2015, Gordon and Pohl, 2011). Many IIAs protect international investors by (1) obligating host countries to provide compensation for directly or indirectly expropriated assets, and/or (2) allowing foreign investors to settle disputes with host countries through compulsory and binding international arbitration (Van Harten, 2007).

Private standards relating to resources – Decision-making concerning resources is influenced by a wide variety of non-governmental standards, in particular those relating to technical specifications and performance; process and management; and measurement and reporting in different sectors (Morrison and Roht-Arriaza, 2007). Key examples relating specifically to resource efficiency are discussed further in Part II - Section 4.3. The development and adoption of private standards concerning resources is influenced by various factors including: demands of business partners and customers; reputational incentives; regulatory incentives; reduction of risks and liabilities; and commercial benefits associated with improved resource management (Morrison and Roht-Arriaza, 2007, Nikolaeva and Bicho, 2011, Henson and Reardon, 2005).

4.3. Governance constraints on resource efficiency and promising responses

The current architecture of global resource governance both enables and constrains different actors' resource efficiency efforts. Current governance frameworks enable such efforts by allocating relevant rights and responsibilities to different actors, and by establishing frameworks for collaboration between these actors. However, several features of global governance currently constrain the ability of relevant actors to work together to use resources more efficiently while ensuring sustainable and socially accepted flows of public and private benefits. Key governance constraints are outlined below, alongside selected promising efforts to address them at local, regional or international scales.

4.3.1. Protection and definition of resource-related rights

Resource efficiency is constrained in many contexts by the fact that rights and obligations concerning resources are not adequately defined, or are not protected in a manner that adequately balances public versus private benefits. Key manifestations of this constraint and several promising responses are summarized below:

Recognition of local community interests – As discussed in Part II - Section 4.2.1, in several countries there are discrepancies between formally recognized rights to resources, and the resource-RELATED expectations and dependencies of local communities. Non-recognition of community interests can disempower local action to improve resource efficiency — particularly where resource-related impacts are not appropriately regulated, or when resource rents are allocated predominantly to formal rights holders (e.g. to TNCs with formal resource development concessions). Promising responses to non-recognition of local community interests include: ongoing legal and policy reforms in several developing countries concerning individual and community land rights (RRI, 2016), the incorporation of social and environmental impact assessments into regulatory decision-making (Vanclay et al., 2015), and the sharing of resource rents with local communities (Barma et al., 2012); the FAO Voluntary Guidelines on the Responsible Governance of Tenure of Land, Fisheries and Forests in the Context of National Food Security (FAO, 2012b); the International Finance Corporation Performance Standards on Environmental and Social Sustainability; the ILO Principles concerning multinational enterprises; the UN Environment Code of Ethics for Chemical Industries; and a growing range of private standards, including the AA1000 Stakeholder Engagement Standard; the Kimberley Process Certification Scheme for diamonds; OECD Due Diligence Guidance for Responsible Supply Chains of Minerals, and supplements; OECD Guidelines for Multinational Enterprises; the ISO 26000 Social Responsibility Standard; the Voluntary Principles on Security and Human Rights in the extractive sector; the Revised Social Accountability 8000 Standard; the ILO Principles concerning multinational enterprises; the Equator Principles; the Global Reporting Initiative Mining and Minerals Supplement; the Conflict-Free Gold Standard; and the Initiative for Responsible Mining Assurance.

Tensions between international investment agreements and national public interests – In several countries, there is widespread concern that IIAs' foreign investor protections (concerning indirect expropriation of investments and compulsory referral of disputes to binding arbitration) unduly constrain the ability of national governments to pursue environmental regulation in the public interest (Beharry and Kuritzky, 2015, UNCTAD, 2015). Indeed, the prospect of an adverse award by an investment arbitration panel has been cited as influential in several national governments' decisions to abandon or change ostensibly public interest regulations concerning the environment and natural resources (Gallagher and Shrestha, 2011, Tienhaara, 2011). On the other hand, promising responses to address potential tensions between IIAs and national public interests include: the progressive integration of specific environmental and social protections into IIAs (Gordon and Pohl, 2011); the OECD Policy Framework for Investment (OECD, 2015c); and the UNCTAD Core Principles for Investment Policymaking for Sustainable Development (UNCTAD, 2015).

Spatial mismatches between resources and rights concerning resources – Observed examples of spatial mismatches between resources and formally recognized resource-related rights include: fragmented property rights to ecosystems (Ruhl et al., 2007); conflicting or unclear superjacent property rights to the land surface and subsurface (Viet et al., 2013); conflicting or unclear rights concerning coastal and offshore areas (Yandle, 2007, Tompkins, 2008); and multiple concurrent or conflicting rights to a particular resource (Deininger and Ali, 2008). These mismatches can impact negatively on resource efficiency by impairing coordination between actors and creating uncertainty and tensions that discourage rights holders from investing in resource stewardship (including resource efficiency). Promising responses to spatial mismatches between resources and resource-related rights are discussed in Part II - Section 4.3.2.

Corruption – In many countries, resource governance is affected by varying degrees of regulatory capture, rent-seeking, bribery and illegal exchange, and other forms of corruption (Leite and Weidmann, 1999, Robbins, 2000, Kolstad and Søreide, 2009, Kolstad and Wiig, 2009). Corruption constrains resource efficiency by misallocating resources and resource rents, and by increasing the cost of the allocation process itself (Liu et al., 2015, OECD, 2013a). A related challenge is the pervasive lack, in some countries, of transparency and meaningful public participation in both government decision-making about resources and the impacts of these decisions on resource-related rights (Darby, 2010). Promising international efforts to reduce corruption and non-transparency in resource governance include the UNDP Global Anti-Corruption Initiative (UNDP, 2014); the Natural Resource Charter (NRGI, 2014); the Publish What You Pay Coalition; the Extractive Industries Transparency Initiative; the Council for Responsible Jewellery Practices; the Global Reporting Initiative; the Transparency Accountability Initiative; and the Open Government Initiative.

Capacity challenges – Governments, communities and individuals in many countries lack sufficient capacity to fully assert or enforce their resource-related rights and interests. Capacity challenges can be technical (e.g. availability of knowledge or qualified experts), social (e.g. level of awareness and education concerning certain issues), financial, or institutional (e.g. structural ability of institutions to coordinate certain actions) in nature (UNDP, 2009, OECD, 2006). Resource governance that features capacity inequalities is at risk of producing inefficiently distributed outcomes, e.g. where unequal bargaining power influences the allocation of resource rents without maximizing aggregate social welfare. This risk is particularly acute in resource development contract negotiations between developing country governments and TNCs (Mitchell, 2013, Gilson, 2012). A wide range of public and private actors are currently working to address these risks through diverse capacity-building and disclosure initiatives. Illustrative examples include the Extractive Industries Transparency Initiative (Haufler, 2010), and IISD Guide to Negotiating Investment Contracts for Farmland and Water (Smaller, 2014).

4.3.2. Coordination across sectors, boundaries and value chains

Efforts to improve resource efficiency are also constrained by uncoordinated decision-making – by different actors, across spatial and sectoral boundaries, or across globalized value chains. A selection of promising responses to these constraints is highlighted below:

Coordinated and measurable action towards common goals – Global resource governance is increasingly informed by data, indicators and targets. These enable diverse actors to assess and coordinate their progress towards common goals – including goals relating to resource efficiency. The relevant goals and targets in the 2030 Agenda for Sustainable Development (see Part II - Section 4.2.3) will therefore be underpinned by the framework of indicators and statistical data designed to monitor implementation progress, inform policy development, and ensure accountability of all stakeholders (UNESC, 2015b). Development of this framework is coordinated by the Inter-Agency and Expert Group on SDG Indicators, composed of United Nations Member States and including regional and international agencies as observers (UNESC, 2015a). At national and regional levels, resource-related data, targets, indicators and associated policy frameworks have proliferated in different policy domains, and across different economic sectors (Bahn-Walkowiak and Steger, 2015, GTZ et al., 2006). Illustrative examples include: "A resource-efficient Europe" — a flagship initiative under the European Union's Europe 2020 Strategy (EC, 2011d, EC, 2011c); China's 2009 Circular Economy Promotion Law and associated policies (West et al., 2013); and policies implemented under the United States Energy Independence and Security Act of 2007 (Fritsche et al., 2013). The European Commission has developed a "Resource efficiency scoreboard", including a suite of indicators designed to assess progress towards relevant European Union policy goals (EC, 2015b). In order to accurately assess progress towards resource efficiency, the full range of costs, benefits and impacts associated with resource development and use must be comprehensively taken into account. Promising measurement and accounting efforts to address this challenge are discussed in Part II - Section 4.3.3.

Coordination across spatial boundaries – A diverse range of resource-related transboundary cooperation agreements were surveyed in Part II - Section 4.2. Notwithstanding the promising progress that these represent, major gaps remain in cooperative resource management across spatial jurisdictional boundaries at national, regional and international scales. These gaps contribute to: inefficient use of land (UN Environment, 2014a), water (UN Environment, 2012d) and various other resources; transboundary pollution (Lee et al., 2016); uncoordinated regulation by governments of transnational actors; and tensions and conflict associated with competing or conflicting claims to resources (UNFT, 2012, Schofield, 2012). An illustrative example of the scale of resource cooperation challenges is that 158 of the world's 263 transboundary water basins lack any type of cooperative management framework (WWAP, 2015). In addition to the international and regional examples discussed in Part II - Section 4.2, promising responses to spatial coordination challenges include the progressive implementation in a growing number of countries of: participatory spatial planning; catchment-based approaches to water governance; community and landscape-level land governance; and integrated coastal zone management.

Coordination across sectors – Efforts to improve resource efficiency are also impaired by the prevalence of decision-making isolated along sectoral lines. In many countries, governmental decision-making concerning resources is characterized by a multiplicity of sectoral mandates and institutions (e.g. agriculture, energy, water fisheries) which are not well coordinated or defined, or may overlap in relation to particular resources (Galaz et al., 2010, Charles, 2012). A related challenge is the prevalence of uncoordinated decision-making between public, private and third-sector actors. At a national level, promising efforts to foster cross-sectoral coordination include the growing range of: national institutions with specific crosscutting or coordinating mandates; public administration procedures designed to develop "whole of government" and "participatory" decision-making; public participation frameworks (see Part II - Section 4.2); and integrative framing concepts such as "the resource nexus" (Ringler et al., 2013), "sustainable development", and "planetary boundaries" (Rockström et al., 2009a). These concepts are designed to transcend sectoral mandates and thereby establish a conceptual basis for cross-sectoral data management, objective-setting and decision-making. Coordination across sectors is also an important issue at the multilateral level, with decision-making being shared across the multiple institutions surveyed in Part II - Section 4.2, and influenced by the multiple surveyed normative frameworks. A promising development in this context is the emergence of "coherence" agendas — championed by UN Environment, the Global Legislators Organisation, and others (UN Environment, 2012a, UN Environment, 2015f). Their principal aims are to ensure: (1) coordinated, efficient and mutually supportive operation of the multilateral institutions with mandates relating to sustainable development; and (2) coherent and mutually reinforcing implementation at a national level of key international agreements, including the UNFCCC, Sendai Framework for Disaster Risk Reduction, and the 2030 Agenda for Sustainable Development.

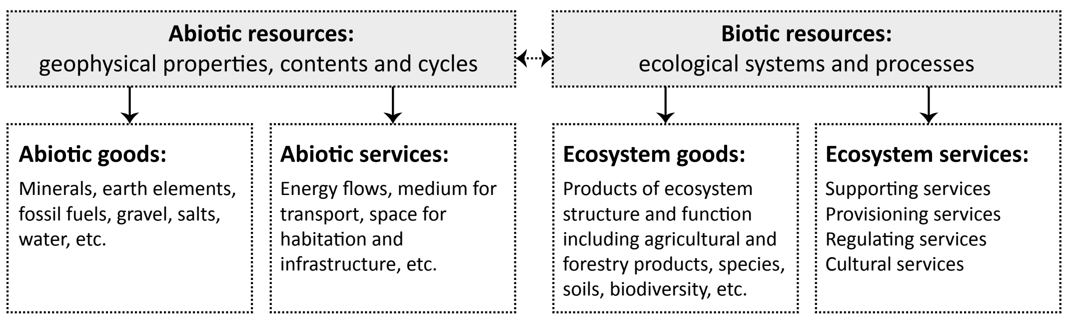
Coordination across value chains – Efforts to improve the resource efficiency of value chains are in many cases complicated by their complex globalized nature, internal power structures (see Part II - Section 4.2.3), and the inability of involved actors to access accurate and complete information concerning resource dependencies in the relevant value chain(s). Governance of several global value chains is becoming increasingly coordinated, in particular as a result of cross-sectoral collaboration between public, private and third-sector actors. Relevant promising efforts in addition to those already identified in Part II - Section 4.3.1 include: the United Nations Global Compact; the GRI Sustainability Reporting Guidelines; the ICMM Sustainable Development Framework; the Global e-Sustainability Initiative; the ICMM Toolkit; ISO/TC 207 concerning environmental management; the ISO 14001 EMS standard; Standards for a Sustainable World; product certification schemes such as the Marine Stewardship Council and Forest Stewardship Council; and pollution-related standards such as the GHG Protocol and Verified Carbon Standard.

4.3.3. Recognition of multiple benefits of resources

Scientific and economic research has characterized, with increasing granularity, the physical stock of resources and their multiple, many irreplaceable, contributions to human well-being and development (MEA, 2005, Kumar, 2012, UK-NCC, 2013, Mace et al., 2015). Figure 55 illustrates the range of benefits provided to people by biotic and abiotic resources.

Efforts to improve resource efficiency are constrained by the fact that only some of these benefits are currently measured, valued in markets, or otherwise taken into account during public and private sector decision-making. Conventional approaches to measuring and managing economic activity do not adequately account for the range of resource stocks and associated benefit flows, particularly critical flows of ecosystem services (Stiglitz et al., 2009, Kumar, 2012). The status of resource stocks and benefit flows is not, for example, captured comprehensively by accounting frameworks such as the United Nations System of National Accounts (EC et al., 2009) or by the ubiquitous and politically influential measure of national economic activity: Gross Domestic Product.

Figure 55: Multiple benefit flows from resources



Source: Authors, adapted from Milligan et al. (2014).

Without holistic identification of the multiple benefits provided by resources, the efficiency of resource use cannot be accurately assessed. Efforts have proliferated in recent years to recognize the multiple public and private benefits of resources in decision-making, and to incentivize multiple actors to invest in long-term maintenance and efficient use of these benefits. Key examples of promising international efforts include:

- *International commitments and goals* – including relevant commitments in Agenda 21; Aichi Biodiversity Targets under the CBD; the Jakarta Charter on Business and Biodiversity; the Gaborone Declaration for Sustainability in Africa; the Natural Capital Communiqué; the 2012 Protocol adopted by the Global Legislators Organisation; the G8 Kobe 3R Action Plan (OECD, 2008b) and the 2030 Agenda for Sustainable Development, as discussed above (Milligan et al., 2014).
- *Measurement and accounting frameworks* – including the Inclusive Wealth Report and associated Inclusive Wealth Index; the World Bank's Adjusted Net Savings; the Natural Capital Protocol for business; and the United Nations System of Environmental-Economic Accounting (SEEA). SEEA is designed to supplement the System of National Accounts, and contains internationally agreed standards for producing comparable statistics on the environment and its relationship with the economy (UN et al., 2014a, UN et al., 2014b).
- *Knowledge and capacity-building partnerships* – including UN-REDD; UN-Habitat; the C40 Cities Climate Leadership Group; the World Bank WAVES Partnership; The Economics of Ecosystems and Biodiversity (TEEB) Initiative; WBCSD and the Natural Capital Coalition; and the 10YFP.

4.4. Towards better governance for resource efficiency

This chapter has outlined the diverse ways in which global resource governance is beginning to respond to the urgent need to improve resource efficiency, including as a subcomponent of wider efforts to improve the sustainability of resource use. These changes are apparent at local, national, regional and global scales, in both developed and developing countries. Despite considerable progress, they currently fall far short of the level of change required to achieve the international community's shared vision of sustainable development.

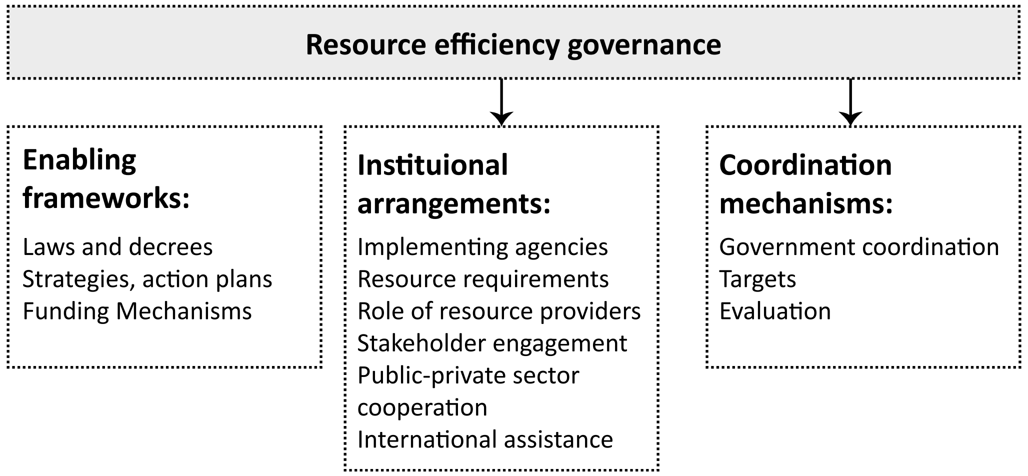
Given the trends outlined in Part I - Section 1.1, meeting future demand for resources will require dramatic improvements in resource efficiency. Due to path dependencies, inertia and other biases against change, these improvements will not emerge inevitably from the operation of markets alone (see Part II - Chapter 3, as well as UN Environment, 2014b).

In the absence of adequate market-led improvements in resource efficiency, change will need to be enabled and driven by appropriate reforms to current features of global resource governance. This includes continued reforms concerning the protection and definition of resource-related rights, management of resources across sectors, boundaries and global value chains, and recognition supported by measurement, valuation and other approaches of the multiple public and private benefits of resources. Figure 56 shows some of the key aspects of energy efficiency governance that will need to be introduced in order to address the various extensively documented barriers to greater increases in energy efficiency (see IEA(2010b) and IEA (2010a), as well as references in Part II - Chapter 3), and by extension greater resource efficiency more generally.

On the basis of the above considerations, the key concluding messages of this chapter are as follows:

- Efforts to remove governance constraints to resource efficiency rely on continued cooperation and diverse forms of support. This entails *international and regional efforts*, including commitments and goals such as the

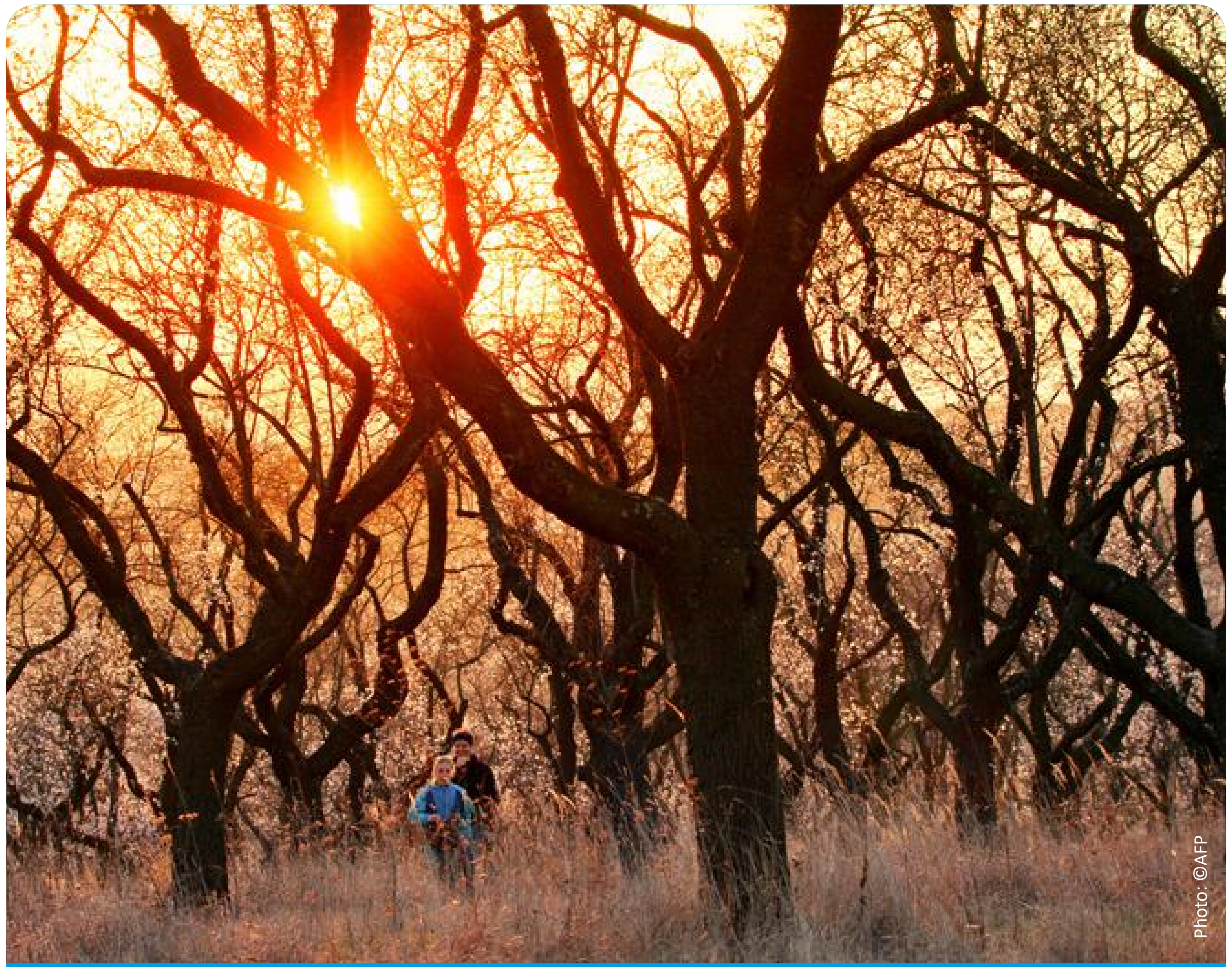
Figure 56: Key aspects of resource efficiency governance



Source: Energy Efficiency Governance Handbook, IEA (2010b) pp. 8–11.

2030 Agenda for Sustainable Development; capacity-building and research partnerships such as the 10YFP; and the implementation at multiple scales of appropriate governance reforms. It also entails complementary *national and subnational efforts* involving various parts of government and other actors, including communities and the private sector. Inclusive cross-sectoral partnerships are crucial to achieving the level of consensus and investment required to ensure lasting and effective reform.

- There is no single “best practice” approach to improving global governance for resource efficiency. The task is complex and specific to regional, national and local circumstances, cutting across many policies, programmes, institutions and sectors. The changes surveyed in Part II - Sections 4.2 and 4.3 represent promising examples that may be adapted to suit different contexts, or larger or smaller scales. Appropriate capacity development of governance frameworks at national, subnational and local scales, and more inclusive participatory processes at local community scales, represent important components of any best practice.
- A key future challenge is to expand efforts to develop and share innovative approaches concerning resource efficiency governance. This chapter has offered a glimpse into the wealth of relevant knowledge and expertise within the collective experience of experts, communities and institutions around the world. Transnational sharing, discussion and synthesis of different approaches to resource governance enables all participating actors to benefit from the global collective experience, and to overcome key barriers to change including knowledge gaps, capacity challenges, or the absence of supportive political commitment. Supported by UN Environment, the OECD, 10YFP and others, the G7 Alliance for Resource Efficiency is well placed to support and facilitate such a process moving forward.



PART III: INCREASING RESOURCE EFFICIENCY: BEST PRACTICES AND CASE STUDIES

The third part of this report considers how resource efficiency can be improved, through looking at examples of best practices and case studies.

There are numerous international programmes and initiatives to increase resource efficiency, and even more at national levels. Three major examples, which have supplied some of the case studies in subsequent chapters, are briefly mentioned here. They exemplify what public policy and committed corporate and citizen action can achieve.

Sustainable Consumption and Production (SCP)

One of the most systematic approaches to increasing resource efficiency has been through the concept of Sustainable Consumption and Production (SCP). The 10-Year Framework of Programmes on Sustainable Consumption and Production Patterns (10YFP) was adopted at the Rio+20 Conference in 2012, and is the explicit subject of SDG 12. Given its global reach and importance, it is discussed in some detail in the next chapter.

The Global Programme on Resource Efficient and Cleaner Production (RECP)

The RECP Programme arose from collaboration between UN Environment and the United Nations Industrial Development Organization (UNIDO) in the 1990s. It seeks to improve industrial productivity while reducing industry's dependence on natural resources and diminishing the generation of waste and harmful emissions. There are now around 60 National Cleaner Production Centres in developing and transition economies in five regions around the world. These centres pursue RECP practices in many countries through concepts such as eco-efficiency, waste minimization, pollution prevention, and green productivity. 2010 saw the establishment of RECPnet, a network linking over 70 institutions that provide RECP services and seek to drive forward innovation and collaboration in RECP (UN Environment, 2016c, UNIDO and UN Environment, 2015).

UNIDO's RECP activities include eco-industrial parks, industrial waste minimization, the transfer of environmentally sound technologies, innovative chemicals management including chemical leasing, new business models and water stewardship. The UN Environment's RECP work concentrates on life-cycle based approaches, product and organizational footprinting, responsible production and safe management of chemicals, eco-innovation, eco-labelling and corporate reporting (UN Environment, 2016c, UNIDO and UN Environment, 2015).

The circular economy

The idea of a circular economy is now principally promoted by the Ellen MacArthur Foundation, which states: "A circular economy is one that is restorative and regenerative by design, and which aims to keep products, components and materials at their highest utility and value at all times, distinguishing between technical and biological cycles" (EMF, 2016b).

The Foundation operates through a number of programmes relating to business, government, education and communication. Its Project Mainstream is led by the CEOs of nine global businesses and aims to accelerate and scale up moves towards a circular economy. Its Circular Economy 100 programme (CE100) brings together businesses, governments, cities and universities to build capacity around the circular economy.

The chapters in this part of the report first showcase some of the positive resource experiences that have been achieved through the 10YFP on SCP (Part III -Chapter 1), before moving on to other best practice examples and case studies of resource efficiency, organized by theme or sector (Part III - Chapters 2-7).

1. SUSTAINABLE CONSUMPTION AND PRODUCTION (SCP)

1.1. Background

The issue of SCP has been on the international agenda since the conclusion of the United Nations Conference on Environment and Development (UNCED) in 1992. As part of the UNCED follow-up process to define an SCP policy agenda, two meetings held in Oslo significantly shaped the discussion on SCP. The Oslo Symposium on Sustainable Consumption in January 1994 identified some of the key areas for action and proposed a working definition of sustainable consumption as "the use of goods and services that respond to basic needs and bring a better quality of life while minimizing the use of natural resources, toxic materials and emissions of waste and pollutants over the life cycle, so as not to jeopardize the needs of future generations" (IISD, 1995).

The Oslo Symposium was followed by the Oslo Ministerial Roundtable on Sustainable Production and Consumption in 1995, which further developed this definition: "Sustainable consumption is an umbrella term that brings together a number of key issues, such as meeting needs, enhancing the quality of life, *improving resource efficiency*, increasing the use of renewable energy sources, minimising waste, taking a life cycle perspective and taking into account the equity dimension" (emphasis added). The round table identified as a key issue "the extent to which necessary improvements in environmental quality can be achieved through the substitution of more efficient and less polluting goods and services (patterns of consumption), rather than through reduction in the volumes of goods and services (levels of consumption)" (IISD, 1995). Such emphasis on resource efficiency (RE) acknowledged the political reality that it would be much easier to change consumption patterns than reduce consumption volumes. Governments and businesses that have approached the SCP agenda have thus done so by accepting the need for changes in consumption and production patterns while retaining standards of living and enhancing economic competitiveness and performance (IISD, 1994).

In 2002, the World Summit on Sustainable Development (WSSD) was held in Johannesburg. Its outcomes included the Johannesburg Plan of Implementation (JPOI), which resolved to "encourage and promote the development of a 10-year framework of programmes in support of regional and national initiatives to accelerate the shift towards sustainable consumption and production to promote social and economic development within the carrying capacity of ecosystems by addressing and, where appropriate, delinking economic growth and environmental degradation through improving efficiency and sustainability in the use of resources and production processes and reducing resource degradation, pollution and waste."

Since the WSSD, two concepts have become central to the discourse on resource efficiency and SCP: decoupling and leapfrogging. The first, as noted above, is the "delinking" of economic growth and environmental degradation, which is now more often referred to as *decoupling* the growth in production and consumption of goods and services from resource depletion and environmental degradation, as discussed in Part I - Chapter 2.

The second concept, "leapfrogging", was developed theoretically in Tukker (2005). This is the idea that developing countries do not need to sequentially follow the patterns of development, either of consumption or production, of industrial countries. Rather, opportunities may exist for developing countries to leapfrog over certain less-resource-efficient and more-polluting development stages, infrastructures or technologies initially utilized by industrial countries, by moving straight to new policies and technologies that sidestep that development pathway. This can occur either by learning from subsequent advancements in developed countries or through indigenous innovations in developing countries, which have the potential to feed back into developed country markets. In order to support SCP, these new policies and technologies can help establish consumption and production patterns that are more resource-efficient and avoid the often costly environmental damage that has characterized the development path of industrial countries.

A review of the leapfrogging concept and its numerous possibilities and challenges for Africa, and for developing countries more generally, was commissioned by the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (Assefa, n.d.). It highlighted the potential to help accelerate the process of development by using advanced systems, saving on infrastructure costs, increasing competitiveness, avoiding environmental damage and learning from experiences of capturing the potential social benefits for its population. Africa's natural resource endowment, low level of technological development and corporate establishment, and limited infrastructural expansion were seen as major opportunities, with success already having been experienced in the solar and ICT industries. However, challenges were identified with regard to the global economic structure, low levels of education, and lock-in problems. Another study (Switch-Asia, n.d.) identified three major areas as prime candidates for leapfrogging: mobile phones (where leapfrogging has already largely taken place in developing countries); organic and localized agriculture; and renewable energy systems.

In response to the JPOI, the United Nations Environment Programme and the United Nations Department of Economic and Social Affairs (UN DESA) established and served as secretariat to the Marrakech Process on Sustainable Consumption and Production. This process provided inputs for the development of the 10-Year Framework of Programmes on Sustainable Consumption and Production (10YFP), which was adopted at the Rio+20 Conference. Encapsulated in the outcome document, "The Future We Want", are the commitment to SCP as a key driver for poverty eradication and sustainable development, and to the 10YFP as a mechanism for achieving this shift in consumption and production patterns.

Another key outcome of the Rio+20 Conference was the UN General Assembly decision establishing the open working groups for the development of the SDGs, provided for in paragraphs 245–251 of "The Future We Want". The SDGs build on the Millennium Development Goals (MDGs). Discussions on and targets related to SCP have been integral to the development of the SDGs; indeed, the inability of the MDGs to address sustainable patterns of consumption and production was seen as one of their limitations (UN, 2013). Different options for incorporating SCP were considered as part of the development process (UN Environment, 2014e). Box 3 contains the text of SDG 12 on SCP and its associated targets. Other SDGs and associated targets relevant to resources and the environment are discussed in Part IV - Chapter 1.

1.2. Implementing the 10YFP

The 10YFP programmes are organized around thematic areas and aim to build capacity to implement policies, voluntary instruments, management practices, information and awareness-raising activities to promote the shift to SCP patterns. The programmes have clear objectives, activities and indicators of performance and success (UN Environment, 2014c). The following six programmes have so far been identified:

1. Sustainable Public Procurement (SPP)
2. Consumer Information Programme (CIP)
3. Sustainable Tourism, including ecotourism, Programme (STP)
4. Sustainable Lifestyles and Education (SLE)
5. Sustainable Buildings and Construction (SBC)
6. Sustainable Food Systems (SFS)

Box 3: Sustainable Development Goal and Targets on SCP (SDG 12)

GOAL

SDG 12: Ensure sustainable consumption and production patterns

TARGETS

12.1: Implement the 10-year framework of programmes on sustainable consumption and production, all countries taking action, with developed countries taking the lead, taking into account the development and capabilities of developing countries

12.2: By 2030, achieve the sustainable management and efficient use of natural resources

12.3: By 2030, halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses

12.4: By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimize their adverse impacts on human health and the environment

12.5: By 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse

12.6: Encourage companies, especially large and transnational companies, to adopt sustainable practices and to integrate sustainability information into their reporting cycle

12.7: Promote public procurement practices that are sustainable, in accordance with national policies and priorities

12.8: By 2030, ensure that people everywhere have the relevant information and awareness for sustainable development and lifestyles in harmony with nature

12.a: Support developing countries to strengthen their scientific and technological capacity to move towards more sustainable patterns of consumption and production

12.b: Develop and implement tools to monitor sustainable development impacts for sustainable tourism that creates jobs and promotes local culture and products

12.c: Rationalize inefficient fossil-fuel subsidies that encourage wasteful consumption by removing market distortions, in accordance with national circumstances, including by restructuring taxation and phasing out those harmful subsidies, where they exist, to reflect their environmental impacts, taking fully into account the specific needs and conditions of developing countries and minimizing the possible adverse impacts on their development in a manner that protects the poor and the affected communities

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

1.2.1. Sustainable Public Procurement

Sustainable public procurement enables public bodies to contribute to sustainable development. This involves considering the entire life cycle of products and services, taking into account their environmental and social, as well as economic, impacts (Melissen and Reinders, 2012).

Public procurement accounts for between 8 and 30 percent of a country's GDP (10–15 percent in OECD countries) (APCC, 2007, UN Environment, 2009a), which gives governments and other public sector bodies substantial opportunity to foster the SDGs (Meehan and Bryde, 2011). Box 4 gives details of a public procurement energy efficiency initiative carried out by the Indian Railways.

Criteria for sustainable procurement have been established on city (e.g. the EU Smart Cities), national (e.g. UK Government Buying Standards or German Blue Angel GPP criteria), regional (e.g. Procura+ criteria for Europe) and global (e.g. SUN project) scales. However, the holistic perspective proposed by the concept of sustainable public procurement (SPP) demands large amounts of information, which hinders its implementation. In addition, governments often find themselves overwhelmed by the complexity of purchasing decisions; they must evaluate products across a range of different sustainability performance criteria (Hutchins and Sutherland, 2008), in addition to the usual considerations of price, availability and operational performance. The combination of prevailing inflexible budgetary mechanisms and bureaucratic procedures, the lack of monitoring and evaluation opportunities, and a general low public appreciation of the efforts by public bodies, goes a long way towards explaining reports of inertia in respect of sustainable procurement in the public sector (Meehan and Bryde, 2011).

Factors that can overcome these barriers to SPP can be broadly clustered into four categories (Brammer and Walker, 2011).

First, displaying the authorities' commitment to more sustainable governance mechanisms (FOEN, 2011, UN Environment, 2009a) can act as a trigger for action in SPp. This is especially true if SPP becomes one component of a general reform of procurement processes (perhaps when a government has to renew and renegotiate contractual agreements) and if legal frameworks are in place to support the inclusion of social and environmental criteria in procurement processes (UN Environment, 2012c). This was the case when developing an SPP policy and action plan in Ghana, where it was estimated that the public sector could save US$ 64 million in energy bills annually, and 2.8 million tonnes of carbon emission over 30 years, by following sustainable procurement standards for purchasing air conditioners (Perera, 2012). In Korea, the Act on Encouragement of Purchase of Green Products in 2004 (discussed in more detail below) stimulated the market for eco-labelled products in public procurement, leading to an increase in purchases from KRW254.9 billion in 2004 to KRW1,727 billion in 2012. Within the same period, certified products (with the Korean Eco-label) increased by a factor of 3.8 (OECD, 2014b).

Second, making the perceived costs and benefits of the policy explicit is also central to increasing knowledge about SPP's effectiveness in promoting sustainable development, which is one of the objectives of the 10YFP for SPp. Displaying an environmentally and socially responsible governance strategy is one of the potential benefits for governments, although the visibility and impact of SPP actions often depends on their scale. For example, SPP can relate to small actions such as using fair-trade coffee in government offices, or larger ones, such as improving the energy efficiency of office buildings. Products and services of the IT, energy, transport and building sectors are considered to have a high impact in this regard.

A third influencing factor is relevant officials' unfamiliarity with SPP policies. As one objective of the 10YFP reflects, it is crucial to build the case for SPP by improving the knowledge

Box 4: Public procurement energy efficiency initiative by the Indian Railways

As Part of the Indian Railways Vision 2020, which aims to increase energy efficiency by 15 percent and to use low-carbon technologies, Indian Railways took a life-cycle approach to replace the inefficient incandescent lamps (ICLs), which are used by many employees that live in railway colonies and lead to peak demand in the evenings. Through intense stakeholder participation and by highlighting the life-cycle costs of different lighting technologies (see Table 6), they managed to distribute 1.41 million energy-efficient compact fluorescent lamps (CFLs) across India in 2009, benefiting more than 400,000 households and saving around 90,000 tonnes of carbon emissions per year (OECD, 2014b).

Table 6: Comparison of life-cycle costing for compact fluorescent lamps and incandescent lamps

Wattage of incandescent lamps	Wattage of compact fluorescent lamps of equivalent lumen	Consumption of electricity in burning incandescent lamps for 6,000 hours = wattage x hours/1,000 KWH	Consumption of electricity in burning compact fluorescent lamps for 6,000 hours = wattage x hours/1,000 KWH	Saving electricity over life cycle of compact fluorescent lamps, i.e. burning for 6,000 hours = (3-4)	Cost of electricity per KWH (in INR)	Savings on electricity bill over life cycle of compact fluorescent lamps = 5*6	Initial cost of each incandescent lamp (in INR)	Initial cost of compact fluorescent lamp of equivalent lumen (in INR)	Initial cost of burning incandescent lamp for 6,000 hours (in INR)	Net savings per compact fluorescent lamp over life cycle (in INR) = 7-9+10
1	2	3	4	5	6	7	8	9	10	11
100	20	600	120	480	5	2,400	15	130	90	2,360
100	23	600	138	462	5	2,310	15	130	90	2,270
60	14	360	84	276	5	1,380	11	90	66	1,356

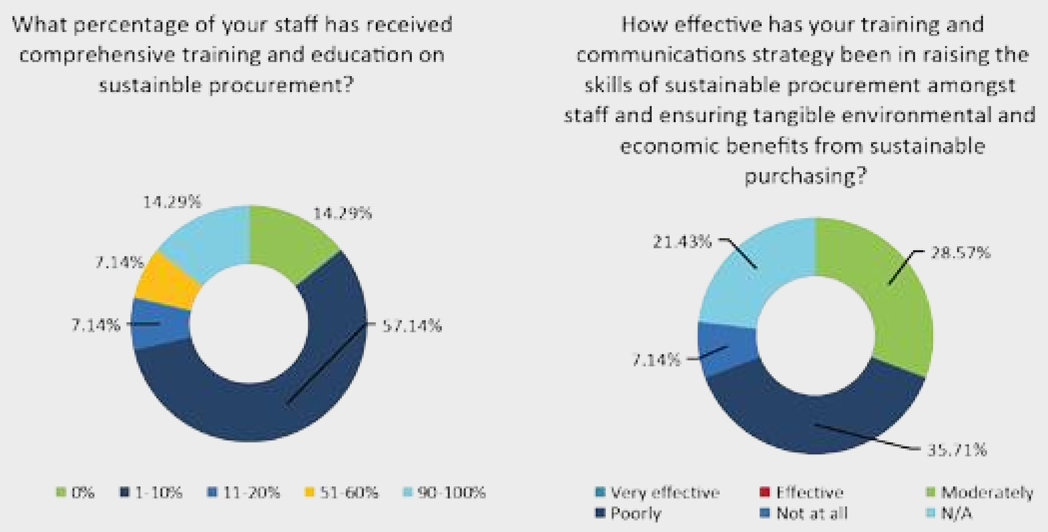
Assumptions:
Life of compact fluorescent lamp - 6,000 hours
Life of incandescent lamp - 1,000 hours

Source: OECD (2014b).

Box 5: Training for Sustainable Procurement in Canadian Municipalities

In a report to evaluate sustainable procurement in Canadian municipalities, the authors found that too little training is provided to staff, and that repeated training opportunities are needed in particular to improve the effectiveness of current education and communication efforts (see Figure 57).

Figure 57: Training and communications regarding Sustainable Procurement in Canadian Municipalities



Source: Reeve Consulting (2014).

base, as organizations need to have the skills, competencies and tools to implement SPp. Given the complexity of sustainable development and the trade-offs and synergies that become apparent when purchasing decisions have to be made, it is not surprising that many procurement professionals consider themselves ill-equipped to manage SPP (Brammer and Walker, 2011). This issue is also exemplified in Box 5.

Finally, the availability of supplies can be a limiting factor, especially regarding specialized products such as medical equipment for hospitals. Purchasing decisions can only be made if there is a certain level of market readiness and products and services are available and standardized (Brammer and Walker, 2011, UN Environment, 2012c).

The Marrakech Task Force on Sustainable Public Procurement developed a now widely-known approach for national governments of both developed and developing countries, which is being tested in a number of pilot countries, including Mauritius, Colombia and Lebanon. The approach consists of a step-by-step methodology, including an assessment of the current situation, an analysis of the legislative framework, a market-readiness analysis, the derivation of sustainability indicators and policies (the current

stage for most countries) and the monitoring and implementation of SPP policies.

Finally, the availability of supplies can be a limiting factor, especially regarding specialized products such as medical equipment for hospitals. Purchasing decisions can only be made if there is a certain level of market readiness and products and services are available and standardized (Brammer and Walker, 2011, UN Environment, 2012c).

The Marrakech Task Force on Sustainable Public Procurement developed a now widely-known approach for national governments of both developed and developing countries, which is being tested in a number of pilot countries, including Mauritius, Colombia and Lebanon. The approach consists of a step-by-step methodology, including an assessment of the current situation, an analysis of the legislative framework, a market-readiness analysis, the derivation of sustainability indicators and policies (the current stage for most countries) and the monitoring and implementation of SPP policies.

1.2.2. Consumer Information Programme

Consumer information on sustainability and resource efficiency aims to guide consumers in their daily purchasing decisions so that they can make informed choices regarding sustainable and resource-efficient goods and services. It stimulates sustainable consumption and hence creates a market and demand for sustainable goods and services.

Certification and labelling are among the most important consumer information tools. Labelling can be considered an "information-providing policy", and even when mandatory on product suppliers, consumers are free to use the information to change their consumption patterns voluntarily (Shen and Saijo, 2009).

Initiated in the late 1980s with the first certified and labelled fair-trade products, certification and labelling now cover a wide range of sectors and issues. Primarily (although not exclusively) driven by NGOs, often in collaboration with industry and community representatives, these voluntary initiatives rely on stimulating preferential consumer choices to drive better environmental and social performance. The fair-trade initiative is focused on social justice issues — seeking, for example, to ensure a fair price for farmers disadvantaged by existing trade systems. However, its successors — such as the Forest Stewardship Council, Marine Stewardship Council and Roundtable for Responsible Palm Oil to name but a few — also include an environmental aspect (in full or in part).

Labels may also address characteristics of products in use rather than production. For example, the Nordic Swan in Nordic countries covers 63 product groups and its assessment processes cover the full life cycle of the products.

Energy labels in the home appliances sector, such as Energy Star in the US, promote energy-efficient products. By making consumers aware of the energy performance of appliances before their purchase, these labels can inform purchasing decisions (Sammer and Wüstenhagen, 2006, Heinzle and Wüstenhagen, 2012). They effectively bridge the information gap between consumers and manufacturers of consumer goods (Shen and Saijo, 2009, Heinzle and Wüstenhagen, 2012) and are intended to create market incentives for appliance manufacturers to design more energy-efficient products, reinforcing price-induced technological innovation (Mills and Schleich, 2010).

The European Union also has an energy efficiency labelling scheme implemented across the EU. Applied to all white goods, home appliances and light bulbs sold within the EU, the scheme came into effect on 1 January 1995 through the Energy Labelling Directive (ELD). The purpose of the label is to allow consumers to compare appliances, which are rated on a letter scale (Sammer and Wüstenhagen, 2006).

Analysis indicates that this mandatory label has successfully penetrated the market. For example,

Box 6: Green public procurement in Korea

In 2004, the Korean Ministry of Environment (MoE) passed an Act to encourage the purchase of green products through the promotion of green public procurement. Its objective was to "prevent wasteful use of resources and environmental pollution, and to contribute to sustainable development in the domestic economy by encouraging environment-friendly product purchasing". Under the Act, public agencies have to purchase environmentally sustainable products directly as well as through service contracts for, for example, cleaning, building repairs and maintenance. The Act defines green products as those that are: (a) certified or meet the criteria set by Korea Eco-label, (b) certified or meet the criteria of the quality certificate for recycled products (Good Recycled Mark) or (c) in compliance with other environmental criteria set by MoE in consultation with the heads of relevant ministries.

Before the Act, about 750 products were certified by Korea Eco-label in 2003. In 2005, following its enactment, this had increased to more than 2,700 products, and has been progressing steadily ever since, with almost 7,800 products certified in 2011. Thus the Act has had a significant impact on the market.

Table 7 shows an evaluation of the environmental and economic impact of the scheme between 2006 and 2011. It indicates success with regard to financial savings, job creation, and reducing carbon emissions, with much potential remaining for expansion into more of the Korean government's procurement activities.

Table 7: Impacts of the Korean Act on Green Public Procurement and the associated Eco-labelling scheme

	2006	2007	2008	2009	2010	2011
KEITI indicators (from KONEPS and directly reported by authorities)						
Total expenditure on green products (billion KRW)	861.4	1,343.7	1,584	1,629.6	1,641.2	1,645.5
% GPP over the global expenditure for 33 selected product groups					53.7	59.5
Reduction of CO_2 equivalent emission from the shorter list of green products (in thousand of tons)	316	495	601	620	538	544
Economic benefits linked to CO_2 emissions reductions (billion KRW)	4.8	7.5	9.1	9.4	8.1	8.2
Job creation (individuals)	737	4,775	2,379	451	115	33
PPS indicator (only purchases through KONEPS)						
% of GPP over the total (domestic) purchases executed by PPS	5.2	6.3	6.2	5.9	5.0	5.5

Source: SCPRAC (n.d.); Querol & Schaefer (2013).

the share of refrigerators meeting the highest energy efficiency labelling classes (A and above) increased from less than 5 percent in 1995 to more than 90 percent in 2010. An evaluation of the ELD undertaken in 2011 on behalf of the European Commission reported: "the ELD has been a success in terms of many products reaching the highest energy performance categories. It has been estimated that these changes have saved 14Mt of CO_2 annually over the period 1996–2004" (Williams et al., 2011). Associated savings for consumers on their energy bills by 2020 are anticipated to amount to some €100 billion annually — about €465 per household.[10]

Labelling may also be linked to public procurement, as shown by an example from Korea, described in Box 6.

1.2.3. Sustainable Tourism

Over one billion people travelled internationally in 2013, equivalent to one person in every seven in the world making an international trip (WTTC, 2014). By 2030, the number of international travellers is expected to reach 1.8 billion (UNWTO, 2011). Tourism is a major economic sector, both in developed and developing countries, accounting for an estimated 9.5 percent of global GDP and directly employing 3 percent of the world's workforce in 2013. Tourism to low-income countries is growing, with 40 percent of international holidays now including a visit to a developing country (UN Environment and UNWTO, 2012). This growth, combined with tourism's potential to create jobs and stimulate the local economy, could make it a driver for poverty reduction and development in such countries.

Tourism can positively or negatively impact environmental and cultural resources. Positive effects include the protection of flora and fauna, and the conservation of historic and archaeological sites, whereas negative impacts include water, air and noise pollution, landscape degradation and biodiversity loss. Under current

10 http://ec.europa.eu/energy/en/topics/energy-efficiency

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

policies and practices, by 2050, growth in the worldwide tourism sector is projected to entail a 154 percent increase in energy consumption, a 131 percent rise in greenhouse gas emissions, and a 152 percent increase in water consumption (UN Environment and UNWTO, 2012).

The dependence of tourism on relatively pristine natural environments and a variety of renewable and non-renewable resources highlights the importance of managing tourism in a sustainable and resource-efficient way. Sustainability should be a major factor when considering tourism planning, investment, operations and management.

Sustainable tourism takes full account of its current and future economic, social and environmental impacts, while addressing the needs of tourists, the industry, environment and host communities (UNWTO, 2010). It appears in the growing number of community-based ecotourism initiatives, with community-based tourism defined as where "the local community has substantial control over and involvement in its development and management, and a major proportion of the benefits remain within the community" (WWF, 2001). The business model behind community-based ecotourism is based on equitable benefit-sharing, through incomes and skills development, and the preservation of ecological and cultural resources by the people who are familiar with and affected by them. Ecotourism has been growing at a rate of 20–25 percent a year (Ballantyne and Packer, 2013), with one estimate suggesting that ecotourism accounted for 7 percent of all tourism globally in 2007 (CREST, n.d.).

Investment in sustainable tourism can enhance the competitiveness of businesses in the travel and tourism sector and of tourist-destination countries, by fulfilling travellers' demands for a reasonably priced visit to well preserved environments. Research by one of the world's largest tourism companies, TUI, found that half of the 4,000 holidaymakers surveyed would book a more sustainable holiday if it was available, and two thirds want tour operators to be clearer about how they make holidays more sustainable (CREST, 2013).

The demand for more sustainable tourism is also reflected by market surveys and in initiatives promoting sustainable and resource-efficient tourism. These include the Rainforest Alliance's programme in Latin America between 2007 and 2011 to enhance the competitiveness and international exposure of micro-, small- and medium-scale sustainable tourism enterprises in Latin America, as briefly described in Box 7.

Some large hotel chains have taken their own initiatives to reduce their energy

Box 7: Rainforest Alliance programme for sustainable tourism in Latin America

The project benefited 396 hotels and providers of other tourism services, and 183 tour operators. During its term, participating hotels and service providers increased their overall sales by 29 percent and occupancy rates by 12 percent. Tour operators who participated throughout the four years increased their sales by 41 percent. In a study of 14 of the participating hotels in five countries, the Rainforest Alliance found that businesses adopting sustainable tourism practices reduced their operating costs. In the participating companies, water consumption and solid-waste production each fell by 71 percent, while energy consumption decreased by 93 percent.

About two thirds of the hotels reduced their water consumption by investing in improved equipment or infrastructure, including the installation of pumps, wells, pipes or an improved sewage system. Leak control and detection systems, composting toilets, low-flow showers, commercial washing machines and/or low-capacity toilet tanks were adopted by 44 percent of the hotels. These practices resulted in annual average financial savings of US$2,718.

Electricity consumption was reduced in 90 percent of the hotels, through the installation of fans, efficient air conditioners, gas driers, water heaters and energy-saving light bulbs, as well as investment in wiring improvements, solar-heating systems for swimming pools, heat insulation and natural cooling systems. Energy savings reduced expenditure by an average of US$5,255 a year per enterprise.

Source: Rainforest Alliance, 2010, Rainforest Alliance, 2013.

Box 8: Energy efficiency improvements by AccorHotels Group

The AccorHotels Group operates over 4,000 hotels worldwide. Between 2006 and 2010, it reduced its CO_2 emissions by 5.5 percent and has introduced the Planet 21 Programme, a sustainable development programme that has 21 commitments across seven "pillars": health, nature, carbon, innovation, local, employment and dialogue (Accor, 2013). The programme also includes an information strategy that distributes educational messages to customers.

By the end of 2013, 7 percent of Accor's hotels used renewable energy, including 162 with solar water heating and 232 using biomass, geothermal and other renewable energies. Between 2011 and 2012, overall energy consumption was reduced by 1.6 percent (although the size of the group had increased). Accor's 2013 Sustainable Development Report (Accor, 2013, p. 96) noted that 63 energy efficiency missions had been completed in 20 countries since 2011. These efforts "made it possible to reduce energy use by 84 million kWh and carbon emissions by 34.2 tonnes while generating over €6.5 million in cost savings".

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

consumption by adopting energy-efficient transport and appliances, constructing energy-efficient buildings, and introducing in-house renewable energy production. The example of the AccorHotels Group is given in Box 8.

Such initiatives contribute to the growing evidence that sustainable and resource-efficient tourism is good for business profitability. In fact, TUI's initiatives to improve its own sustainability — by improving management of energy and fuel in its offices and airlines — saved the company nearly GBP£21 million between 2008 and 2011 (CREST, 2013, TUI, 2013). In the same vein, through the Zero Carbon Resorts initiative, small- and medium-sized tourism businesses in the Philippines improved their cost performance by up to 40 percent as a result of improvements in electricity, fuel and water efficiency (EU Switch-Asia, 2014, Wimmer, 2014).

1.2.4. Sustainable Lifestyles and Education

Sustainable lifestyles and education are at the heart of achieving more resource-efficient consumption and production. Consumers' lifestyles create demand for products and services. Education can create awareness about how to use that consumer power effectively, as well as provide the incentive for manufacturers to build more sustainability into their products.

Tukker and Jansen (2006) showed that the three major categories of consumption associated with environmental impacts are housing, transport and food (for example, in EU countries these three categories cause 70 percent of environmental impacts, while comprising only 57 percent of expenditure). This report addresses food systems in detail in Part III - Chapter 4, and buildings and construction are discussed in the next section. This section gives two brief case studies of urban lifestyles, which are discussed in more detail in Part III - Chapter 3 and are of particular importance for resource efficiency. The density of the living space, the opportunities for effective public transport systems, the potential of sustainable urban regeneration and the high numbers of individuals that can be impacted by urban campaigns provide great opportunities for more resource-efficient urban lifestyles.

Following these case studies, the issue of middle-class lifestyles is addressed, given the burgeoning growth of the middle class in many emerging and developing economies.

1.2.4.1. Low-income urban mobility

One of the key challenges facing low-income urban dwellers is paying the travel costs to access employment many miles from their homes. This is particularly challenging in the emerging megacities. In 1990, the Municipality of Lima in Peru took an innovative approach to make resource-efficient transport more affordable for low-income households, by setting up a micro-credit programme to help low-income citizens purchase bicycles. The programme, "Programa de Transporte Popular de Vehiculos No Motorizados", is scheduled to run until 2020.

The main objectives of the programme are to:

- Increase bicycle use as a complementary or alternative means of transport
- Reduce transport costs for low-income groups by facilitating access to bicycles

- Reduce automotive environmental pollution and improve health
- Provide safe, convenient and direct non-motorized transport infrastructure.

As public transportation costs about US$25 per month, workers earning US$200 per month can see their income effectively rise by 8 percent during the loan repayment period and by more than 12 percent once the loan has been paid off (ICLEI – Local Governments for Sustainability et al., 2009).

1.2.4.2. Behaviour change in municipal buildings

Innovative building and infrastructure design can achieve significant energy savings in the urban environment. However, these savings from building technologies can be significantly enhanced by complementary changes in lifestyles, as shown by a project with the Tygerberg Administration building in Parow, Cape Town. Initiated in 2003, the project aimed to reduce energy use, expenditure and GHG emissions through introducing technological interventions and promoting behavioural change among the city staff who used the building. The behavioural change component of the programme involved sending staff members regular informative emails, a display board set up at the entrance of the building displaying savings from the project, information pamphlets and newsletters keeping staff constantly updated on project achievements, and requesting staff to take action to reduce the electricity bill.

The project achieved a saving of 12,000 kWh per month, amounting to an annual saving of 144,000kWh of electricity — a 22 percent saving. This translates to a saving of R39,000 (US$5,159) and 158.4 tonnes of carbon emissions per year. Approximately 14 percent of the savings were achieved through the technical changes, while 8 percent were achieved through staff participation in the behaviour change programme (ICLEI – Local Governments for Sustainability et al., 2009).

1.2.4.3. New markets looking for sustainable and more resource-efficient consumption

The rise of the middle classes in emerging economies has been documented in both the academic and grey literature (Andrew and Yali, 2012, Kharas, 2010, World Economic Forum, 2013, Hubacek et al., 2007, Tuncer, 2013, Wilson, 2013). This effect is particularly evident in the Asian emerging economies given the large populations of these countries (Andrew and Yali, 2012).

China's middle class is already large in absolute terms and surveys of consumer attitudes show that they are eager to become the world's leading consumers. In India, the middle-class boom is only just beginning, with a dramatic projected expansion from a middle class comprising 5–10 percent of its population today to one that comprises 90 percent by 2039 (Kharas, 2010). Significant growth is also anticipated in the middle classes of other Asian economies, such as Indonesia and Vietnam (Andrew and Yali, 2012). Kharas's (2010) assessment of countries closing the income gap with the United States identifies these countries in the "converging" group, alongside Thailand, Cambodia and Malaysia.

As people move from consumption driven by necessity to consumption driven by choice, they have an important influence on the goods and services produced, their production methods, and their impact on economic prosperity, competitiveness and the environment. Such changing lifestyles and consumption patterns have been a common feature of most developing Asian nations in recent decades (Hubacek et al., 2007). This is expected to continue, with increases in global purchasing power associated with the middle classes expected to grow from US$21 trillion to US$56 trillion by 2030, with over 80 percent coming from Asia (Kharas, 2010). This rapid growth of purchasing power, combined with early evidence of this group emulating the unsustainable consumption patterns of more industrialized countries, make the emerging Asian middle classes a critical demographic

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

group for engagement if more resource-efficient lifestyles are to become mainstream among this group (Tuncer, 2013).

The middle class in these emerging Asian economies comprises a younger population compared to their counterparts in the US and Europe (Andrew and Yali, 2012). These rising urban middle-class Asian "millennials" (born between 1981 and 1995) present a great opportunity to exert influence because of their emerging wealth, attitudes and behaviour (World Economic Forum, 2013). There is therefore the potential to induce a "green leap" to a lifestyle less resource-intensive than that of their European and North American counterparts. For example, the Chinese not-for-profit organization JUCCCE is attempting to encourage a new aspirational lifestyle among the new middle classes, replacing the "American Dream" with a more sustainable and resource-efficient "Chinese Dream" (World Economic Forum, 2013).

1.2.5. Sustainable Buildings and Construction

Sustainable Buildings and Construction (SBC) includes the planning, design, commissioning, construction, maintenance, refurbishment and end-of-life stage of buildings. Sustainability in this regard refers to the use of natural resources such as water, energy, minerals, natural materials, and land as well as the quality of the building in terms of its designed purpose, such as a healthy and comfortable living environment. SBC therefore requires frameworks and schemes that facilitate policy implementation and the exercise of skills and techniques to reduce the energy used in producing building materials.

The building sector is economically important in practically all countries, employing 10 percent of the global workforce (De T´Serclaes, 2007) and typically contributing 10–15 percent to countries' GDPs (UNEP-SBCI, 2009). Moreover, in many countries people spend on average 90 percent of their time inside


Photo: ©AFP

buildings and cars (see, for example, Brasche and Bischof (2005) for a detailed analysis in Germany).

In terms of sustainable production, measures frequently relate to technical changes, such as the use of durable, efficient and healthy materials of high construction quality. They focus on the entire production process, in terms of its requirements for both energy and other resources, seeking to improve resource efficiency overall (see, for example, Zhang et al. (2013) for a life-cycle assessment in Hong Kong).

With changing energy costs and the anticipated impacts of climate change, many national and international bodies have seen the necessity to set targets and guidelines for improving the building and construction sectors' energy performance and reducing carbon emissions. On a global scale, buildings are responsible for 38 percent of GHG emissions, 40 percent of annual energy consumption, 12 percent of global potable water use and, in developed countries, 40 percent of solid waste streams (UNEP-SBCI, 2012). Energy use could be reduced by up to 50 percent, and GHG emissions by 35 percent, with net economic benefits in many cases. Water use could be reduced by 40 percent and waste outputs by 70 percent (UNEP-SBCI, 2012). The built environment therefore offers many opportunities for improved social, economic and environmental outcomes and to thus contribute significantly to long-term sustainability overall.

The sustainable consumption literature highlights the need to address different aspects of residents' behaviour in buildings, which can explain much of the variance in energy use in similar buildings (around 50 percent for cooling and 30 percent for heating) (Langevin et al., 2013). For example, improved insulation of the building stock will make it easier to reduce energy demand and residents' energy bills if, in addition, people know how to regulate indoor temperature during the day- and night-time to achieve a comfortable temperature in the most effective way (Verma et al., 2012).

The focus on technical issues regarding materials, construction technologies or design components needs to be complemented by attention to social and economic issues, such as those related to cultural heritage and social equality. This is evidenced in the housing and lifestyle projects from the UN Environment International Environmental Technology Centre (www.unep.org/ietc) and the Collaborating Centre on Sustainable Consumption and Production (http://www.scp-centre.org/). The place-specific context and factors such as ownership rights and land-use restrictions play a central role in defining what sustainable building and construction means in different circumstances, and how it can be best achieved (du Plessis, 2001).

Harnessing the potential for improving energy efficiency in housing requires investments that cannot rely solely on private investment decisions, but rather require individuals, businesses and governments to collaborate. Governmental organizations can support private SBC efforts, for example by stimulating experimentation and innovation, or by providing opportunities for fundamental debates e.g. on technologies and legislation, or that help mechanisms and processes that foster SBC to enter the mainstream and be scaled up (Tukker et al., 2008). This can be achieved by providing financial support to develop new materials, technologies and methods for sustainable building, and by facilitating the uptake of these innovative technologies and methods by producers. It can involve providing subsidies or tax reductions to small businesses for purchasing construction materials, for attending training sessions, and to increase consumers' purchases (e.g. through public housing and financing schemes).

Another important consideration is that a large part of the housing stock is either rented or undergoes regular changes in ownership. Investments that result in long-term benefits are often not a high priority for short-term renters and temporary homeowners. To increase the impacts of sustainable construction and building

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

in low-income areas and to develop the low-energy building stock beyond niche efforts and pioneering sustainability projects by the wealthy, large-scale programmes for financing low-energy buildings have to be developed. These programmes must have a long-term vision and be able to be secured beyond single terms of office (Fuhry and Wells, 2013).

Although energy savings can bring about substantial economic benefits, the technologies to achieve them can require considerable upfront investment. This makes energy-saving mechanisms inaccessible to low-income groups. However, as these groups spend a higher proportion of their annual salaries on energy bills for cooking and heating, they stand to gain the most from energy-saving programmes.

In countries of the Global South, improvements in the building and construction sector are crucial to addressing needs for housing, employment and public infrastructure in a context of rapid urbanization and urban population growth (Persson et al., 2008). Green Mortgages Mexico is an initiative managed by the Institute for the National Workers' Housing Fund (Energy and Climate Partnership of America, 2012, INFONAVIT, 2013, BSHF, 2013). This scheme granted more than 900,000 green mortgages, benefiting more than 3 million people, between 2007 and 2012. Credits targeted primarily towards low-income households have low interest rates (4–10 percent, depending on their income level), which are cross-subsidized by higher-income households. Developers build houses with energy-saving materials and use eco-efficient technologies to improve the service quality of water, electricity and gas. Households enjoy a higher quality of life and save about US$17 on their monthly bills, while spending US$6 more compared with conventional mortgages. On average, water use has decreased by 60 percent, gas by 50 percent and electricity by 40 percent, bringing about reductions of 0.75 tonnes of carbon emissions per household per year. Key aspects for the success of these programmes are the prioritization of low-income dwellers in the receipt of benefits, making programmes easy and free to access and providing short-term social, economic and environmental benefits alongside longer-term ones.

The Residential Energy Program in Boston shows how sustainable housing programmes can reach low-income households in cities in a developed country (see Box 9).

Not only consumers and the environment, but also producers and investors, accrue benefits from sustainable building and construction. Multiple standards and certification systems allow public entities and private companies to position themselves and measure their performance as sustainable producers. BREEAM, the Leadership in Energy and Environmental Design (LEED) programme, Green Star, CASBEE and HK-BEAM are widely used certification schemes. They provide producers with an opportunity to highlight their green standards and position themselves as environmentally friendly in the construction sector (Nguyen and Altan, 2011).

These certificates, alongside other factors such as an increasing awareness of climate change and the potential for cost savings, have also contributed to consumers actively demanding more energy-efficient buildings. A study on green building trends in 60 countries anticipates that "green" will become a business imperative and that the sector will continue the rapid growth seen in recent years: 28 percent of participants in this worldwide study of architects, constructors, engineers, homeowners and consultants indicated that their work focuses on sustainable design and construction. On average, 60 percent of their project work was projected to relate to sustainable, green building and construction by 2015 (compared with 28 percent in 2012). Respondents indicated lower operating costs (76 percent), higher building values (38 percent) and certificates providing quality assurance (38 percent) as major gains of green buildings. In the year following the study, 78 percent of participating firms expect a decrease in operating costs, by a median of

Part III: Increasing resource efficiency: best practices and case studies

Box 9: Residential Energy Programme in Boston

Established by the City's Office of Environmental & Energy Services, the Renew Boston Residential Energy Efficiency Program is a network of energy-efficiency and alternative-energy service providers, City administration, job training organizations and several specialist business and civil society partners. The programme aims to increase energy efficiency and the use of renewable sources in order to reduce CO_2 emissions across the city, including for low-income groups, and create green jobs. Qualified property owners and renters in 1–4 unit buildings can sign up for a no-cost Home Energy Assessment, where they are advised on potential areas for improving their homes (e.g. light bulbs, water saving). Additionally, they can receive significant support (a 0 percent interest HEAT loan for up to 75 percent of the cost, to a maximum of US$2,000) to "weatherize" their homes through measures such as insulation, heating system improvements and air sealing. US$1 million of the City's Grant was allocated to support small businesses, financing up to 70 percent of the total costs for retrofitting lighting and mechanical systems, with a return on investment typically in less than a year.

Home energy assessments and weatherization tripled between 2010 and 2012. Boston aims to reach the entire city through collaborations with grass-roots organizations, strong public engagement, committed leadership by the Mayor and the city government, the ability to attract state, federal and private funding, integration into existing legal and political structures and coordination with other initiatives.

Source: http://www.renewboston.org/

8 percent in the case of new buildings, and 9 percent for retrofitted buildings (McGraw-Hill Construction, 2013). These trends can be seen as part of a broader development trend, where the market for fair and green products and certified labels to inform consumers continuously increases.

The emergence of a large middle class in developing Asian countries is greatly increasing the demand for houses. For example, in India, where 22 percent of all energy is used by the residential sector, increased building and construction is — with current practices — expected to lead to an eightfold increase in the sector's overall energy use by 2050, compared with 2012. However, the Global Buildings Performance Network has shown how an aggressive policy and market-driven strategy could reduce energy consumption by 57 percent relative to these projections. This would require a 30 percent penetration of the Energy Conservation Building Code standards, moderate air conditioning and significant appliance-efficiency improvements (GBPN, 2014).

Improved resource efficiency in production methods can reduce local air pollution as well as CO_2 emissions. In Bangladesh, about 1,000 (authorized) kilns operate in six districts, producing about 3.5 billion bricks annually in the Greater Dhaka region by using coal and agricultural waste as fuel. Calculations show that their emissions include 302,000 tonnes of carbon monoxide, 15,500 tonnes of sulphur dioxide, and 1.8 million tonnes of CO_2 and they are said to be responsible for about 5,000 premature deaths per year due to air pollution (Guttikunda et al., 2013).

Green Bricks Bangladesh,[11] which promotes smokeless brick fabrication while also increasing productivity, has shown how a change in the production of construction material can have significant impacts on energy use and pollution, especially if the change is implemented in the whole country. In comparison with traditional brick fabrication, Green Bricks require only about one third of the amount of coal and a single improved kiln, that can produce up to 15 million bricks, can cut CO_2 emissions by 5,000 tonnes annually (Hossain and Abdullah, 2012). It was estimated that the 15 demonstration kilns built by the Green Bricks project in Bangladesh would save 314,000 tonnes CO_2 equivalent by the end of the project in 2015. The ongoing replacement of the old technology of brick fabrication throughout Bangladesh will benefit not only the heavily polluted environment and climate, but also workers' health and income (UNDP Bangladesh, 2010).

Economic benefits also result from the more stable, year-round workloads and the "green jobs" created by this new technology, which is particularly beneficial for previously seasonal workers. Additionally, new skills and knowledge are gained. It was estimated that by the end of 2014, 15 demonstration factories would facilitate the knowledge transfer of the new brick-making technology by training workers, operators and managers from about 100 existing factories (Saha and Rahman, 2013).

In India, the Towards Zero Carbon Development (T-Zed) project in Bangalore was initiated by a private company (Biodiversity Conservation India) to build a gated community of 16 houses and 75 apartments. Numerous technological innovations in the development reduce energy consumption (e.g. for air conditioning and refrigeration) and increase self-sufficiency in an area occupied by higher-income residents. Additionally, the project encourages residents to lead low-carbon lifestyles and engage in water- and energy-saving, organic-vegetable growing and community activities (Bulkeley et al., 2011).

Other examples show that demands for greater energy efficiency must be met not only by single building and construction projects, but also more systematically, at a large spatial scale and comprising multiple types of uses. For example, buildings in the Beddington Zero Energy Development (BedZED) community in the UK use 60 percent less energy compared with average homes in this area, and water consumption is 58 percent lower than average. Energy savings come from built-in solutions such as high insulation levels and photovoltaic panels, while water use is reduced through installing low-use washing machines and dual-flush toilets. In addition, lifestyle changes have increased recycling rates and led to sustainable food choices. Estimates suggest that this can translate into GBP£3,258 annual savings on transport, water and energy bills for a three-person household using an on-site club car, compared with an average London household. The construction process itself promotes sustainability through both the materials used and their transportation. Fifty-two percent of the materials (by weight) were sourced within 56 km, and 15 percent of the construction material (3,400 tonnes) was reclaimed or recycled. The economic value of the eco homes is 5-10 percent higher than other houses in the area. [12]

In another example, the Public Housing Fund in Ljubljana, Slovenia, manages about 3,300 municipally owned non-profit units (about 3 percent of the stock). Aiming for high-quality refurbishment and construction, particularly in less well-off areas of Ljubljana, this project significantly reduces households' energy

11 http://www.bd.undp.org/content/bangladesh/en/home/operations/projects/environment_and_energy/improving-kiln-efficiency-in-brick-making-industry-/
12 See http://www.bioregional.com/bedzed/

consumption while increasing people's self-esteem. For example, a 1,000m² post-war apartment block with 20 flats was retrofitted, with a particular focus on ventilation and insulation systems, as well as on raising awareness of energy-saving lifestyles. After the retrofitting, energy consumption fell from 75–85 kWh/m² to 50 kWh/m² annually (LG Action, n.d.).

Building resource efficiency is a major priority to ensure that current global urbanization processes do not lead to a massive expansion of resource use and the associated negative environmental impacts. It is, however, not the only element of urbanization that will have a critical impact on resource and environmental outcomes. Others include wider considerations of urban design and infrastructure (Part III - Chapter 3), and how to achieve resource-efficient mobility (Part III - Chapter 5).

1.2.6. Sustainable Food Systems

In resource terms, about 25 percent of the world's habitable land is used for food production, which also accounts for 70 percent of all freshwater withdrawals and 80 percent of deforestation (Moomaw et al., 2012). Agriculture is responsible for around 10–12 percent of all greenhouse gas emissions and is the largest contributor of non-CO_2 emissions (Smith et al., 2014). Emissions from soils and methane from livestock account for about 70 percent of total agricultural greenhouse gas emissions. Paddy rice cultivation, the burning of biomass, synthetic fertilizers and manure are also significant sources of agricultural emissions. The impact of food systems upon the environment and the growing demand for more food indicate a need to develop food systems that are more resource-efficient while also contributing to improving the livelihoods of many vulnerable people (FAO, 2012a).

Ensuring that food systems are sustainable and resource-efficient requires consideration of the life cycle of food products, from production to consumption. It also entails addressing issues such as lifestyles and diets, food losses and waste, the distribution of agricultural incomes, methods of processing and transport, and practices and behaviours that have adverse impacts on the environment.


Photo: ©AFP

Agricultural practices largely determine the sustainability of food production. Sustainable agriculture is driven by local knowledge and resource-conserving techniques, and in developing countries practices such as integrated pest and nutrition management, water harvesting and minimum tillage, have been shown to increase yields and improve the nutritional value of food, as well as conserve soils (Pretty et al., 2011, Altieri et al., 2011, FAO, 2014b).

As discussed further in Part III - Chapter 4, food waste deeply compromises the sustainability of food consumption. Globally, one third of all food produced is lost to waste (Moomaw et al., 2012). In

developing countries, this waste occurs mainly at the post-harvest stage of the food system (i.e. processing and storage), while in high-income countries it is at the retail and household consumption stages.

Holistic approaches are required in order to tackle food system problems at the global level and to ensure close coordination between the public and private sectors. The public sector can contribute by creating a regulatory and fiscal environment that drives consumers and producers towards sustainable food systems. This may include promoting sustainable products through regulatory and fiscal instruments, while contributing to marketing and public-awareness initiatives about sustainable food and diets to influence well-informed consumers' food consumption (Moomaw et al., 2012, FAO, 2012a, HLTF, 2012). Initiatives that provide a platform for cooperation between public sector and private companies involved in the industry are also important. Examples include public procurement from companies adopting sustainable practices, and certification schemes and eco-labelling. This not only has the potential to address agricultural value chains through integrating producers and consumers, but also to increase the competitiveness of the private companies involved (Moomaw et al., 2012).

Food producers can increase their productivity by sustainably intensifying production or by diversifying production. Intensification is defined as increased physical or financial productivity from existing resources. It can be achieved sustainably through, for example, improved varieties and breeds, utilization of unused or under-used resources, improved labour productivity, and changes in farm management. Diversification is defined as a change in the pattern of agricultural production, including

Part III: Increasing resource efficiency: best practices and case studies

exploitation of new market opportunities. It may also involve food producers expanding into agro-processing or other farm-based, income-generating activities.

Agricultural development that targets smallholder farms and promotes sustainable practices, such as nutrient and water management, has proved to be effective in increasing productivity and food security, and reducing poverty and environmental degradation (FAO, 2014b). Increased productivity on smallholder farms increases the local demand for goods and services and can have a greater impact on poverty reduction than a similar productivity increase on large-scale mechanized farms. Meanwhile, employment creation in the non-farm sector of rural areas, induced by an increase in smallholder productivity, is a significant contributing factor to the reduction of rural poverty.

After adopting sustainable agricultural practices, over 12 million farmers in 57 developing countries achieved a 79 percent average increase in yields, according to an analysis of 286 agricultural projects (Bossio et al., 2006). The highest increases in yields were on irrigated smallholder farms and in homestead gardens. Similarly, where sustainable agricultural practices had been introduced in 20 countries in sub-Saharan Africa, after periods of 3-10 years, crop yields increased by an average of 2.15 times (Pretty et al., 2011). Increases of 50–100 percent are common after the adoption of sustainable practices (Altieri et al., 2011).

In South-East Asia, sustainable rice production practices have achieved impressive results and rapid uptake (Neate, 2013). Rice is the staple food of over half of the world's population, yet rice farming has some serious environmental drawbacks. Paddy rice consumes more water than any other crop, and globally, nearly 40 percent of all irrigation water is used to grow rice. Flooded rice fields also produce about 10 percent of all the methane produced by human activities, with this greenhouse gas being 25 times more potent than carbon dioxide. Paddy fields are also a significant source of nitrous oxide, from the breakdown of excess nitrogen in the soil. Excessive use of inorganic fertilizers and agrochemicals in rice production is also responsible for environmental damage, such as pollution of water bodies. Producing rice in a more sustainable way thus has the potential to make a major contribution to improving the sustainability of the world's food systems. The Sustainable Rice Platform (www.sustainablerice.org), a multi-stakeholder platform led by UN Environment and the International Rice Research Institute (IRRI), therefore aims to address these issues through a combination of private and public tools and mechanisms to drive the uptake of sustainable technologies and sustainable landscape management.

One form of sustainable rice production is the "System of Rice Intensification" (SRI), first developed in Madagascar in the 1980s. This approach to rice cultivation uses less water and other inputs, and has now spread to more than 50 countries. SRI was introduced to South-East Asia in the 1990s, with impressive results. In Cambodia, yields from fields where SRI has been applied are often double those from traditionally managed paddy, and the production costs are much lower. Financial returns are also higher. In Vietnam, where over 1 million farmers adopted SRI between 2007 and 2011 (Castillo et al., 2012), farmers using SRI have increased their yields on average by 9–15 percent, reduced nitrogen fertilizer use by 20–25 percent and water consumption by a third, used 70–75 percent less seed, and increased their incomes by US$95–260 per hectare each season — equivalent to 7–18 percent of per capita income in 2011. Globally, the SRI website claims that SRI can result in 20–100 percent increased yields, up to a 90 percent reduction in required seed, and up to 50 percent water savings.

Achieving greater resource efficiency in food systems will require shifts away from resource-intensive agricultural practices, inefficient infrastructure, carbon-intensive processing and transport systems, diets requiring the production of resource-intensive food, and avoidable waste.

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

Part III - Chapter 4 provides more details of initiatives and practices that are increasing the sustainability and resource efficiency of the global food system.

1.3. Conclusions

The 10-Year Framework of Programmes on Sustainable Consumption and Production Patterns (10YFP) was given a global mandate in its adoption at the Rio+20 Conference on Sustainable Development. The 10YFP serves to support the widespread adoption of SCP, which is a fundamental component of the post-2015 development agenda. Resource efficiency is, in turn, at the heart of SCP.

The evidence in this chapter shows that moving towards SCP through increased resource efficiency has global relevance, with examples provided from Asia, Europe, South America, Africa and North America. Diversity can also be seen in terms of the economic development of the countries where SCP practices are originating. In more developed economies with high levels of institutional capacity, SCP is largely being generated through public programmes, and city-level initiatives. SCP is also generating success in developing economies, but the model is more commonly (although not exclusively) one that is grass-roots led. SCP can therefore take place within a range of institutional and governance settings.

These diverse approaches indicate high potential for replication and scalability, with adaptation to local circumstances. In some cases, there is strong evidence of this already occurring, while others are still in the demonstration phase. Education and training will be crucial in diffusing SCP practices more widely. Much diversity can also be seen in the leading and participating actors, with the examples above including small- and medium-sized enterprises, large businesses, governments, national and international non-governmental organizations and community groups. However, the mere existence of good SCP practices in one context does not seem, of itself, to engender extended uptake of such practices, and policy and practical realities seem to militate against the simple transfer of good practice from one context to another. This constitutes a problem for the widespread diffusion of SCP, the answer to which has yet to be found.

Another important thread running through the case studies is the importance of a holistic view and addressing production, consumption and mechanisms simultaneously to realize the potential economic benefits. This requires coordination between multiple actors to reach the full scalability potential. Traditional "environmental", "development" or "technological" perspectives will fail to capture the full range of benefits, as they will not connect products and people to receptive markets. In particular, the economic benefits derived from SCP and resource efficiency are key drivers for greater adoption of these approaches, including by private actors, government bodies and individuals.

Overall, the evidence presented here and elsewhere, both from academic research and more anecdotal case studies, suggests that SCP can contribute to a sustainable and equitable economic future in a carbon-constrained world. Nevertheless, much more remains to be done to advance the SCP agenda and maximize its potential.

2. THE 3RS: REDUCING, REUSING AND RECYCLING OF RESOURCES, MATERIALS, PRODUCTS AND WASTE

2.1. Background and overview

This chapter reviews the potential for overarching resource management strategies to enhance resource efficiency across different resource streams and sectors. In particular, it examines "waste hierarchy" or "material management hierarchy" concepts, which promote the integrated use of resource and waste solutions across the supply chain. The order of the

hierarchy indicates an order of preference between the options.

Such strategies involve a holistic understanding of throughputs of material resources over the life cycle of products, from extraction of natural resources, raw material production, parts production, manufacturing, use and operation, through to end-of-life treatment including reuse, recycling, energy recovery and final disposal. The essence of these strategies is to achieve both efficient use of natural resources and environmentally sound management of solid waste, by integrating issues in the upstream (sources for resource inputs) and downstream (sinks for waste and emission outflows) parts of product life cycles. When implemented successfully, such strategies offer reduced resource extraction at the upstream end of the life cycle, as well as reduced impacts associated with waste disposal, land, soil, water and energy use, across the life cycle. In many cases, these broader resource efficiency benefits will also translate to economic benefits for individual companies working within or across the supply chain. In such cases, there are clear economic drivers at the firm level for implementing such strategies. However, whether such economic benefit in fact arises is dependent on how the cost of implementing the resource efficiency strategy compares to the cost of extracting or processing the material without it, and to the cost incurred from any waste or by-products generated by the process. If the economic benefit of the resource efficiency strategy is not clear to the actor concerned, public policy may need to address this barrier to resource efficiency.

2.1.1. The 3Rs and other material management hierarchies

A well-known material management hierarchy summarizes the key resource and waste management options as, in order of preference, "Reduce, Reuse, Recycle" — often referred to as "the 3Rs". This hierarchy has been widely accepted and promoted within both policy and academic circles. It has been broadly adopted within the waste management strategies of a number of countries, including the UK (DoETR, 1995), Japan (Ministry of the Environment, 2005) and the Netherlands (Parto et al., 2007). The essence of the hierarchy is to prioritize the strategies which are the more efficient means to avoiding waste. "Reduce" means avoiding creating unnecessary material in the first place, thereby avoiding not only waste but also the energy and other resources associated with the creation of materials. "Reuse" implies that the energy and other resources used to create materials are made to go further, as the material is used multiple times. "Recycle" is the third tier of the hierarchy, because restructuring materials in recycling processes incurs an energy and resources penalty, and because not all materials can be readily recycled. Allwood (2014) confirms that "'reduce, reuse, recycle'… remains the correct ambition for reducing environmental impact". The IPCC Fourth Assessment Report (IPCC/AR4) identified that "recycling reduces GHG emissions through lower energy demand for production (avoided fossil fuel) and by substitution of recycled feedstocks for virgin materials" (Bogner et al., 2007, paragraph 10.4.5). The IPCC/AR5 further clarified that "the most effective option for mitigation in waste management is waste reduction, followed by re-use and recycling and energy recovery (robust evidence, high agreement)".

The 3Rs is thus a concise summation of the fundamental principles of a resource management hierarchy. It is also, of course, a simple and memorable phrase — an important strength which should not be underestimated. Such phrases provide an easy-to-handle shorthand for important but multifaceted issues, thereby contributing greatly to the communication of such issues within policy discussions and the wider public discourse. However, it would be a mistake to assume that each of these terms stands for a single activity. Rather, each of the terms can be considered as broad and overarching designators for a variety of different activities. The first of the terms, "reduce", could include the avoidance of unnecessary waste generation within product manufacturing by optimizing processes, as well as the potential for absolute reductions in demand for the products themselves, by altering social perceptions of the desirability of material things. The second term, "reuse", also could be specified in more detail. For example, the Gharfalkar et al. (2015) "hierarchy of resource use" distinguishes between various categories of reuse: "reuse without any operation such as repair (e.g. second, third-hand sales, etc.); repair and reuse; refurbish and reuse; recondition and reuse; remanufacture and reuse; any other operation followed by reuse, for example refill and reuse" (Gharfalkar et al., 2015, p. 309). The third term, "recycling", can occur at various stages of the supply chain, involving the participation of different actors and with different associated costs.

Other waste hierarchies extend the 3Rs concept to express the available material management options in slightly more detail. This obviously increases the number of "steps" described by the hierarchy, with the advantage of greater detail coming at a cost of reducing the concept's simplicity, and thus, possibly, its memorability. In the Netherlands, "Lansink's ladder" (Parto et al., 2007) arranges in order of priority: waste prevention, design for waste prevention, product reuse, material recycling, material recovery for use as fuel, incineration, landfill. In Japan, the Sound Material-Cycle Society (SMCS) policy sets out five steps in order of priority: reduce, reuse, recycle, energy recovery and final disposal. Almost the same five steps are adopted by the EU's Waste Framework Directive. Although there are considerable similarities of priority product categories between these two examples, there are some differences in the definitions and boundaries between waste and non-waste in Japan and the EU. Nonetheless, each of these more detailed material management hierarchies is consistent with the "3Rs", if the latter is considered as an overarching concept that can encompass numerous specific strategies within each of its three high-level terms.

2.1.2. Implementation of the 3Rs in national and international policy

In the context of the G7 and G8, the 3Rs concept has played a key role within resource efficiency

strategies. Following the Japanese proposal at the 2003 G8 summit in Evian to enhance understanding of resource and material flows and to continue work on resource productivity indicators, the 3R Initiative to encourage more efficient use of resources and materials was agreed by G8 leaders at the 2004 summit at Sea Island under the US presidency. The 3R Initiative was formally launched at the 3R Ministerial Conference in Tokyo in April 2005 (Moriguchi, 2007, Takiguchi and Takemoto, 2008). In 2008, the Kobe 3R Action Plan was adopted under the Japanese presidency of the G8.

In Japan itself, recycling laws for specific product groups have been enacted for 1) packaging and containers, 2) home appliances, 3) end-of-life vehicles, 4) food, 5) construction and demolition, and most recently, 6) small electronics. Whereas Japan's Home Appliance Recycling Law covered bulky electrical equipment, diverting them from landfill to recycling, the country's more recent recycling act for small electronics aims to recover critical materials.

The EU's recent 2015 circular economy policy package identified five priority areas; 1) plastics, 2) food waste, 3) critical raw materials, 4) construction and demolition, and 5) biomass and bio-based products. In addition, the EU already has legislated Directives for packaging, WEEE (waste electrical and electronic equipment), ELV (end-of-life vehicles) and batteries.

Both Japan's Home Appliance Recycling Law and the EU's WEEE Directive set mandatory targets. The primary goal of these approaches has been to minimize the environmental burden by reducing the amount of waste to be disposed of, and by managing harmful substances. Environmental benefits include reducing demand for landfill space, reducing GHGs and risks from pollutants, and saving natural resources. However, many of these existing strategies have focused on setting targets based on the weight of recovered materials, rather than their economic value. While such approaches can positively affect the recovery of bulk materials, they may have a much smaller effect on the recovery of valuable materials found in smaller quantities, such as the large number of different critical metals found in small quantities in electrical and electronic waste (UN Environment, 2013c).

Furthermore, such approaches have tended to focus on the avoidance of waste going to landfill through recycling, rather than on options that fall within the "reduce" and "reuse" categories (Bulkeley and Gregson, 2009) and, by extension, a more holistic view of resource efficiency and industrial policy. For example, Van Ewijk and Stegemann (2014) and Gharfalkar et al. (2015) question whether the EU's waste hierarchy is sufficiently clear and appropriate not only to reduce waste disposal but also to enhance resource efficiency more generally. In line with this focus of EU legislation, EU Member State policies have tended to focus on regulating or taxing waste to landfill, or on recycling targets, rather than more upstream interventions. Japan's SMCS policy originated from the desire to reduce the financial, social and environmental costs of solid waste disposal, given severe constraints on final disposal capacity. Strengthening the first 2Rs (reduce, reuse) is now being emphasized in the Third Fundamental Plan for Establishing a Sound Material-Cycle Society, as efforts for these 2Rs have been less successful compared to the third R, recycling. There is potential for increased gains in resource efficiency if future approaches also consider industrial supply chain management, eco-design, and product-based approaches such as lifetime extension by direct reuse, repair, refurbishing or remanufacture. Furthermore, governments are becoming increasingly aware of the benefits of moving upward through the resource management hierarchy, and seeing material efficiency policy not just as a fixed target, but as a transition path.

These developments point towards a growing recognition of the potential of more integrated, holistic and life-cycle based approaches to

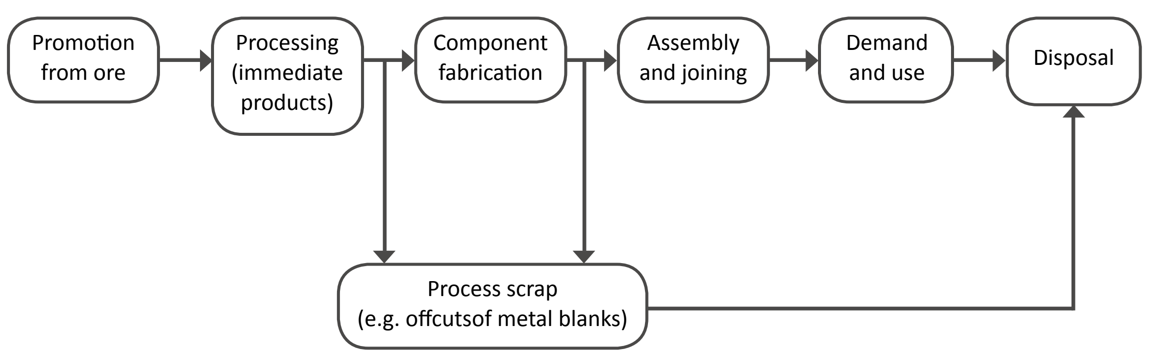
Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

resource and waste management, working through product supply chains. Traditionally, industrial systems have been characterized by fairly linear flows of resources from extraction, through use, to disposal. Figure 58 shows a schematic representation of an extremely linear product supply chain, from extraction to manufacture and end-use, in which material arisings and by-products of manufacturing processes are largely discarded, as are the materials contained in the products themselves, when they reach the end of their lives. In contrast, Figure 58 shows how approaches to improving material efficiency seek to reduce the linearity of resource flows: loops take material rejected from the supply chain and feed it back as a resource into an earlier stage of the supply chain, rather than simply allocating it to a waste stream.

Material that is fed back into a supply chain to be somehow reused reduces both waste disposal and the amount of virgin material that must be extracted. The opportunities for profitable value recovery for businesses from such material feedback loops have been explored within the concept of "closed loop supply chains" (Guide and Van Wassenhove, 2009). If such feedback processes were maximized, it would be theoretically possible to have a material economy that created no waste and required no extractive activity, but constantly reused its material assets: a "circular economy".

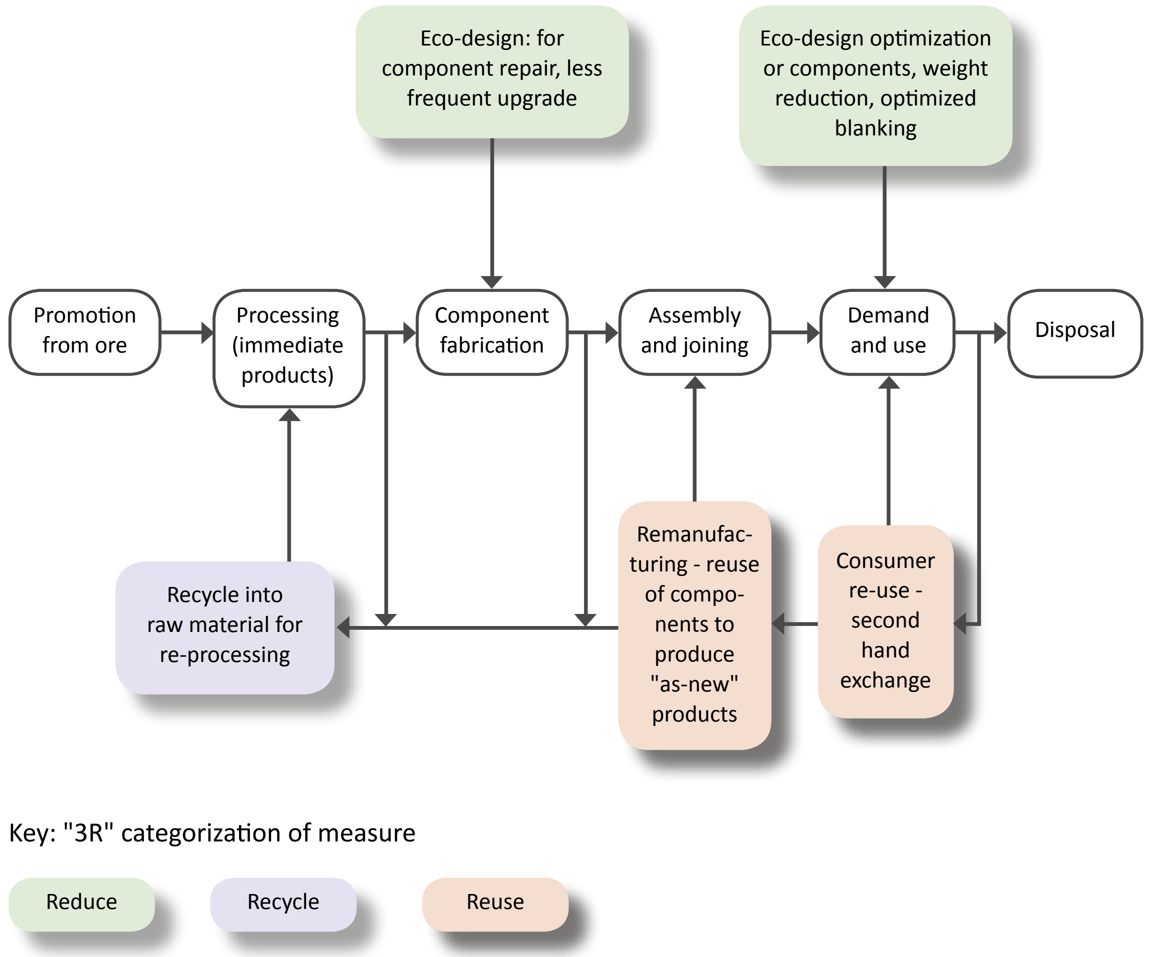
This concept has been explored and promoted recently by the Ellen MacArthur Foundation (EMF, 2015). It can also be traced through various national policy efforts over a number of years, including Germany's Closed Substance Cycle Waste Management Act (1994) (German Law Archive, 2013), Japan's Fundamental Plan for Establishing a Sound Material Society (2003) (Ministry of the Environment, 2003) and China's Circular Economy Promotion Law (2008) (PPPIRC, 2016). As such, there is a link between resource efficiency, waste hierarchy and circular economy concepts. Thus, the co-chairs of the OECD-UNEP 2008 Resource Efficiency Conference stated that "the different concepts and approaches are converging: 3Rs, sound material-cycle society, circular economy, integrated or sustainable waste management, sustainable consumption & production, life-cycle management and sustainable materials or resource management, all aim at similar objectives and require similar action by the various stakeholders" (Mwandosya and Namiki, 2008).

Figure 58: Schematic representation of a highly linear product supply chain



Source: adapted from OECD (2008) and Allwood et al. (2011).

Figure 59: Schematic representation of a more "circular" resource-efficient product supply chain, showing the benefits of the "3Rs"



Source: adapted from OECD (2008a) and Allwood et al. (2011).

In response to a request from the G8 Environment Ministers, OECD published an interim evaluation of progress in 2011 (OECD, 2011). This presented key trends and main policy developments related to resource productivity, and set out policy principles for sustainable materials management and key lessons for policy making. During the COP21 in Paris, the International Resource Panel delivered 10 Key Messages on Climate Change. Message 2 reads: "Decoupling economic growth from environmental and resource degradation, and creating a circular economy through reuse, recycling, and remanufacturing are key strategies for reducing both GHG emissions and other environmental and resource pressures" (UN Environment, 2015c).

The following sections review in more detail the potential of the various approaches outlined in Part II - Section 6.1 and schematized in Figure 59. Each type of approach has the potential to increase the efficiency of material use, but each also has its limitations, thus further emphasizing the need for integrated thinking. These sections consider in turn the broad categories of the 3Rs: reduce, reuse and recycle. For reasons of space, this report does not address impfacts associated with the extraction and mining of resources, nor with the disposal of any material not captured by the 3R processes, which may also be important.

2.2. Reducing material use

The first pillar of the 3Rs, "reduce", can, as mentioned in Part III - Section 6.1, take on various different forms. This report focuses on ways that material demand can be reduced through more resource-efficient processes, but without incurring a reduction in the services provided. Some approaches to this are now briefly described.

2.2.1. Dematerialization of material service demand

It is possible that new technologies could be used to reduce material use while still meeting material service demands. For example, digital and internet technologies allow users to stream or download films, music or literature as digital content, without needing to physically own a DVD, CD or paper book (Berkhout and Hertin, 2004). However, it is still not easy to establish concrete evidence that digital technologies do directly lead to overall dematerialization. One reason for this is that the technological changes that bring about digitalization often go hand-in-hand with increasing demands for other kinds of associated physical products. For example, Hogg and Jackson's (2009) study of digital music suggests that any material saving arising from the digitalization of the media may be outweighed by the increased material footprint of the upgraded electronic equipment required to play it.

2.2.2. Reduction of materials through intensifying use

Many products, such as privately owned vehicles, sit unused for the vast majority of their lives. In theory, this leaves significant potential for much-reduced production of materials if people were prepared to share their vehicles or other products. However, acting against this are strong social preferences for the convenience of having exclusive access to such products, without having to negotiate with the needs of others. In addition, for many consumers, products such as cars carry a status meaning beyond their purely functional aspects (Jackson, 2009). Nonetheless, car clubs are a growing phenomenon, and may be increasingly viable in urban areas with dense populations and good public transport (Baptista et al., 2014, Dowling and Kent, 2015, Rabbitt and Ghosh, 2013) In addition to cars, PWC (2015) has explored what is coming to be called "the sharing economy" in relation to other retail and consumer goods, hospitality, and entertainment, media and communication.

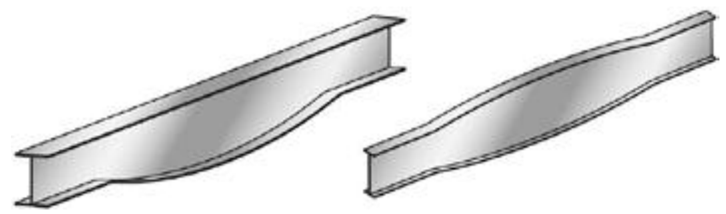
2.2.3. Reducing excess material use through lightweight design

Components of cars and buildings could be made more lightweight if they were optimized for their intended use. For example, material could be saved by producing beams that are thicker and therefore stronger at the points at which they will bear the largest loads, and thinner at less load-bearing points. An illustration of such a design is shown in Figure 60.

However, as optimizing individual components works against mass production's economies of scale, it typically costs more. Furthermore, the effort to monitor numerous different-shaped components adds significant complications at the building site or other point of assembly, compared to dealing with identical and interchangeable parts, thus also increasing costs (Allwood, 2014). Thus, Moynihan and Allwood (2014) found that in a range of commercial London building projects, the materials were over-specified beyond the needs of the safety standards, because the added cost of the materials was less than the increased cost of engineering design time that would be required to achieve a design that met the safety standards with an optimal material mass. UN Environment (2014b) reports the typical over-specification of building mass as being in the

Part III: Increasing resource efficiency: best practices and case studies

Figure 60: Illustrations of optimized "fish belly" designs for steel beams, in which more material is located at the point of the maximum bending moment, with tapered designs reducing material where it is not needed



Source: Carruth and Allwood (2012).

range of 15–30 percent. However, this frequently reflects an economically efficient (if resource inefficient) trade-off between the costs of materials, and the costs of design and logistics. In many situations, "counter to expectations, it makes good business sense to over-specify materials when doing so allows a greater saving in labour costs, and this is a difficult issue to overcome" (Allwood, 2014). Allwood (2014) hopes that advances in computerized production systems and technologies may reduce the cost penalties of component optimization, and that product certification that proclaims embodied energy efficiency of buildings, cars and other products may help stimulate a market-pull for such materially efficient design innovations.

Lightweight design can also be achieved through innovations in the materials themselves. For example, higher-strength steel allows less material to be used without reducing its structural qualities. Steel company ArcelorMittal estimates that higher-strength steel can achieve a 32 percent reduction in the weight of steel columns, and a 19 percent reduction in the weight of steel beams (Dobbs et al., 2011). Moreover, there is considerable scope for gains if this kind of material innovation becomes more widespread, as many countries currently use comparatively low-strength steel. For example, China, which currently consumes 60 percent of global steel reinforcement bar (rebar) production, typically uses lower-strength steel of around 335 MPa for rebars, while Europe uses 400–500 MPa steel in rebars (Dobbs et al., 2011). However, in China the codification of a Design Specification of High Strength Steel Structures is under way, which aims to provide guidance for and promote the use of higher-strength steels, from 460 MPa to 690 MPa (Shi et al., 2016). McKinsey calculates that "if all developed countries moved to a 500 MPa rebar strength and if 50 percent of the use of rebars in developing countries moved to 450 MPa, this would save around 45 million tonnes of steel in 2030" (Dobbs et al., 2011). To the extent that steel could be strengthened even further, this could further increase material savings.

2.2.4. Reducing excess material use through reducing scrap and wastage in production

Ideally, reducing demand would be the first priority of material management strategies, as it reduces the energy use and environmental impacts of extracting and processing materials. In addition, experience in Germany suggests that, with guidance, improving material efficiency can yield quick benefits for some businesses. The German Government's material efficiency agency, demea, offers quantified material flow analysis to help small and medium-sized enterprises (SMEs) identify material savings potentials. On average, companies saved 2.3 percent of annual company turnover, with smaller companies saving a greater proportion. Investments generally paid off within 13 months (UNIDO, 2013).

The mass production of manufactured components from intermediate products, such as sheets or bars of metal, generates large amounts of scrap material, left over after the desired product has been cut, punched or forged from the material. For example, blanking and stamping metal to produce a car door results in half of the original liquid metal being left behind as waste. This causes a doubling in the embodied energy of the part (Allwood, 2014). Again, this kind of resource-inefficient process is driven by the fact that the cost savings in simplified processes and economies of scale outweigh the costs, to the manufacturer, of the lost materials.

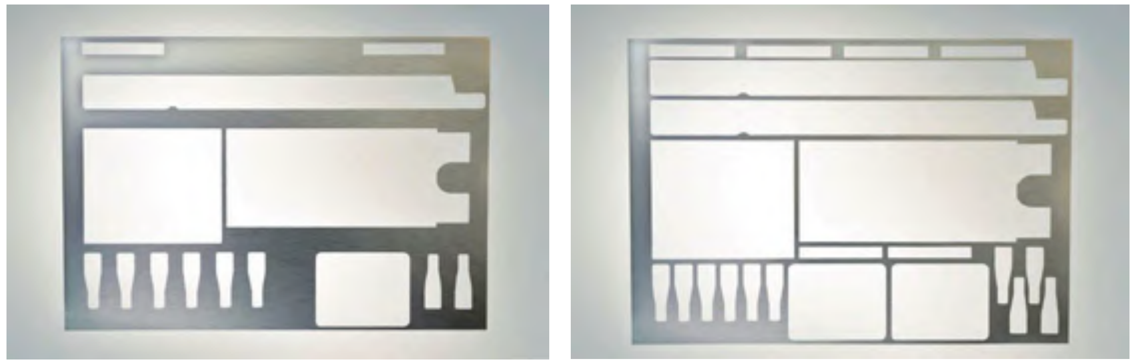
However, such material and energy wastage can be avoided through better design of the arrangement of blanks to fit more closely on a fixed width sheet. Such techniques, already used in the textile industry, are also being adopted for metals (Allwood, 2014, UN Environment, 2014b). Figure 61 illustrates material savings achieved by Deutsche Mechatronics GmbH, an engineering company whose services include measuring and blanking sheet metal for a variety of customers. The company cuts blanks amounting to up to 40 tonnes of sheet metal per day, responding to the orders of up to 100 customers. By using "intelligent shuffling" to fit the parts more closely together on the metal sheet, significant material savings were achieved.

Reduction or avoidance of packaging is another way of reducing material use. In one example, Electrodomésticos Taurus designed a blender whose packaging formed useful parts of the product itself, thereby eliminating cardboard packaging (UN Environment, 2014b)(p. 53).

2.2.5. Reducing materials through material substitution

Bamboo has been proposed as a potential substitute for less sustainable resources, in a range of applications including "co-firing in power plants, producing bio-oil, for food, paper, clothing, furniture, wind turbine blades, sporting equipment, scaffolding and construction" (UN Environment, 2014b, p. 51). Bamboo has a tensile strength reaching 370 MPa, which is comparable to the figure for lower-strength steel quoted by McKinsey (2011); however, its light weight means its ratio of tensile strength to specific weight is six times greater than that of steel (Agarwal et al., 2014). This means that in well-designed buildings, it can be substituted for steel, and produce structures that are wind- and earthquake-resistant (Jayanetti and Follet, 2003). Bamboo is also approximately 50 times less energy-intensive per unit of stress than steel (UN Environment, 2014b, p. 52); Ghavami, 2005). Agarwal et al. (2014) report on experiments that show that, with appropriate treatment, bamboo can be substituted for steel as reinforcement in concrete columns and beams. In addition, Huang et al. (2012) report on experiments on bamboo strengthened with carbon reinforced polymer, also concluding that it has the potential to be substituted for steel substructures in construction.

Figure 61: Left-over sheet metal following blanking of components in an unoptimized arrangement (top), and in an optimized arrangement (bottom), the latter creating much less left-over scrap



Source: Deutsche Mechatronics GmbH, as reported in O'Brien and Miedzinski, 2012.

Moroz et al. (2014) also report that bamboo has great potential as a substitute for steel reinforcement, though with some caveats. Because bamboo's modulus of elasticity — a measure of the stiffness of an elastic material — is similar to that of concrete, "from a theoretical point of view bamboo could never prevent or reduce initial cracking in flexure" (Moroz et al., 2014). Such factors may limit the potential for bamboo to be used to reinforce high-capacity structures. The authors also note that if bamboo absorbs moisture while it is being set in the concrete, it can expand and cause cracks in the concrete. Care must therefore be taken to avoid this, for example by treating the bamboo with waterproof coating. Further research is required on the performance of bamboo-reinforced masonry within different building components, on the long-term properties of bamboo-reinforced masonry, and on the performance of bamboo reinforcement within the locally produced concrete blocks of different countries, which may have varying properties (Moroz et al., 2014).

A range of other materials could potentially be replaced with inputs derived from renewable biomass, including chemicals, plastics and other materials currently derived from fossil fuels. However, it will also be important to consider that there could be potentially negative impacts of replacing non-renewable with renewable resources, for example through increased demand for land and related impacts on ecosystems and biodiversity (Bos et al., 2016).

2.2.6. Reducing materials through innovative technologies

More substantial material reductions in product manufacturing may be possible through innovative design approaches. An important development in this regard may be advances in 3D printing, or "additive manufacturing" (AM). This allows highly customized components to be produced to specification in a manner that significantly reduces material wastage. General Electric is now producing nozzles for jet engines in this manner, with significant material savings reducing the weight of the component by 25 percent (Despeisse and Ford, 2015). Huang et al. (2016) analyse weight-saving potential from the use of AM in a range of selected aircraft components, estimating the total mass reduction potential at 4–7% of the average aircraft empty mass.

2.3. Reusing materials

Reuse is the next level of the 3Rs, preferable to "recycling" due to the additional energy penalties incurred by the latter. As already noted, the "reuse" category can cover a range of activities, from second-hand markets, return or reuse of packaging and containers, to more technologically innovative processes of component reassembly, such as "remanufacturing".

2.3.1. Remanufacturing

At the industrial level, there is considerable interest in a form of reuse now known as "remanufacturing". Remanufacturing involves taking a used product and restoring it to like-new or even better condition. This aspect importantly distinguishes remanufacturing from the reuse or resale of second-hand objects, which are not expected to have "as-new" qualities, and will have reduced or no warranty as a result. The intention of remanufacturing is to deliver "a product with the same quality level, performance with the same or more technical features, the same endurance and warranty" as the equivalent new product (Steinhilper and Weiland, 2015).

Remanufacturing is a developing sector of global trade, with the United States and Europe currently responsible for the majority of remanufacturing activities and global trade. In 2011, the United States was the largest remanufacturing nation globally, when the value of its remanufactured production was US$43 billion, and its exports of remanufactured goods totalled US$11.7 billion. Its major remanufacturing sectors were "aerospace, consumer products, electrical apparatus, heavy-duty and off-road equipment, information technology products, locomotives, machinery, medical devices, motor vehicle parts, office furniture, restaurant equipment and retreaded tires" (USITC, 2012). A number of other countries are developing their remanufacturing industries, however barriers to trade include "regulatory barriers, import bans, and the lack of a common definition of remanufactured goods" (USITC, 2012).

Remanufacturing can deliver notable resource efficiency by reducing the amount of raw materials used in manufacturing as well as industrial waste and energy use. The raw materials saved through remanufacturing cut back on the energy and thus emissions required to extract materials and process them. On average, the production of remanufactured goods consumes significantly less energy than comparable new ones. Additionally, through remanufacturing, non-renewable resources remain in circulation for multiple lifetimes, conserving significant volumes of the raw materials, labour, and embodied energy in the product. Steinhilper and Weiland (2015) draw on cross-industry studies to suggest that, on average, remanufacturing achieves energy savings of 50 percent and material savings of 80 percent compared with new production. Nasr (2010) suggests that in some cases, the ratio of energy required for original production compared with that required for remanufacturing can be as much as six to one. In a more specific example, it is estimated that a typical large-scale automotive factory with a remanufacturing process could save up to 105,000 MWh of energy, 240 tonnes of copper, 440 tonnes of aluminium and 2,200 tonnes of steel per year (Steinhilper and Weiland, 2015). Such savings in energy and materials may translate into economic benefits for firms implementing such strategies, yet as remanufacturing is generally more labour intensive, it can result in net job creation (Matsumoto et al., 2016). Whether the approach as a whole is profitable therefore depends critically on the relative costs of labour and materials.

The remanufacturing process includes: collection of cores (defined by the remanufacturing industry as used products or sub-systems in economically remanufacturable condition), disassembly, cleaning, inspection, repair, replacement of worn-out parts, reassembly, and testing (Matsumoto et al., 2016, Steinhilper and Weiland, 2015). Once remanufactured, a product re-enters into use. Such a product may be remanufactured several times, enabling multiple useful lifetimes before it becomes too worn to be economically remanufactured again.

Remanufacturing is already undertaken in a number of areas. Remanufacturing of automobile parts is currently the largest remanufacturing sector globally (Matsumoto et al., 2016), including engine parts (McKenna et al., 2013, Smith and Keoleian, 2004, Sutherland et al., 2008, Seitz, 2007) and tyres (Amin et al., 2017, Subulan et al., 2015, Ferrer, 1997). Other sectors include household appliances (Sundin and Bras, 2005), packaging (Tsiliyannis, 2005), aviation, aerospace, hospital equipment (Steinhilper and Weiland, 2015), and fashion and textiles (Dissanayake and Sinha, 2015). Printer cartridges can also be remanufactured, with the process potentially providing attractive ongoing sources of revenue for original equipment manufacturers (OEMs) (Francie et al., 2015, Jung and Hwang, 2011).

Barriers to remanufacturing arise when the product design inhibits an efficient remanufacturing process. Sundin and Bras (2005) analyse remanufacturing facilities for household appliances and automotive parts, and find that the cleaning and repair stages have the greatest effect on the process' overall efficiency. They thus suggest that to facilitate remanufacturing, products should be designed to allow ease of access, ease of handling, ease of separation and wear resistance. Meanwhile, Sundin et al. (2012) explore the potential for automated disassembly of products. This could aid remanufacturing not only by reducing costs, but also by reducing human contact with toxic and harmful substances. However, here again product design can be a major inhibiting factor, especially as products become more complex and heterogeneous, use more proprietary components, and change rapidly with successive product generations. As such, an important objective is to encourage companies to ensure that products are designed with end-of-life considerations in mind (Sundin et al., 2012). Customer understanding and recognition of remanufactured products is also a key barrier, as is legislation that acknowledges remanufactured products and their "as-new" qualities (Wei et al., 2015, USITC, 2012).

2.3.2. Reuse of industry waste and offcuts

Offcuts left over from blanking sheets of materials could be reused by other manufacturers who need to cut smaller pieces from the same type of material. Abbey Steel in Kettering in the UK has found such a niche, purchasing blanking scrap from car body manufacturers and using it to cut smaller blanks for other manufacturers. This business niche is available because of car manufacturers' relatively inefficient use of metal; if they used laser-cutting techniques to optimize the fit of blanks from a given sheet, the niche might disappear. An alternative take on this would be "to coordinate blanking requirements over a much wider range of customers" (Allwood, 2014).

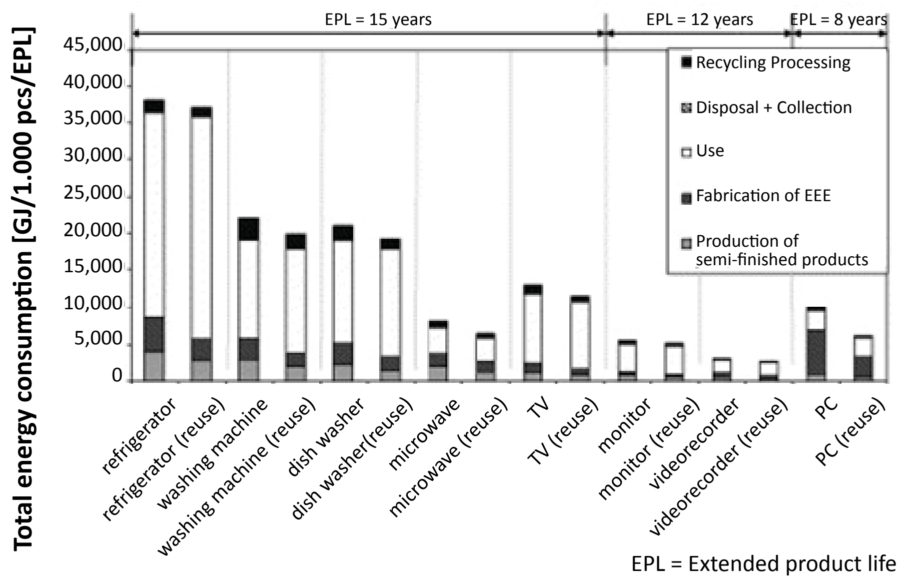
2.3.3. Exchange, second-hand trading and repair

Opportunities for reuse through exchange and second-hand trading exist in a variety of forms across most economies. These can include well-established and well-regulated second-hand markets for products such as houses and cars (Allwood, 2014). Other items such as clothing, books, furniture and household items are also amenable to second-hand exchange. Some second-hand goods may have high value due to being antique or otherwise collectable. For low-value goods, the transaction costs are usually too high for individuals to trade them, which has traditionally provided a niche for charity shops. However, in recent years the growth of online shopping and exchange forums has provided another means of undertaking exchanges (Castellani et al., 2015). These developments mean that an increasingly wide variety of goods can be traded between individuals with minimal transaction costs. Woolridge et al. (2006) report on a life-cycle assessment study which confirms that the reuse of donated waste textiles via charity shops does result in an energy benefit compared with the production of clothes from virgin materials, even accounting for the energy that the charity expends on collecting and distributing the textiles. Castellani et al. (2015) carried out a case study on the cumulative avoided impacts of a second-hand shop, finding that the sale of clothing was the largest contributor to the shop's avoided environmental impact per year, with the second largest category being furniture. Although fewer furniture items were sold during the year, each item was responsible for a large avoided impact.

For energy-consuming goods, there can be interesting trade-offs between the savings in embodied energy from repairing or otherwise extending the life of a product, and the savings in energy use that occur if the product is replaced and upgraded with a newer, more energy-efficient version. Whether life extension or replacement is the more energy-efficient option varies greatly across different product types and other contextual factors. In one study of automobile use in Japan during the 1990–2000 period, Kagawa et al. (2008) found that life extension of existing vehicles had greater environmental benefits than replacement with new vehicles with higher fuel economy, because of the embodied energy in manufacturing the new vehicles.

Truttman and Rechberger (2006) focus on domestic appliances, comparing two scenarios of a hypothetical system over 15 years in Figure 62. This shows the total life-cycle energy consumption for eight domestic appliances over their respective potential extended product lives. In one scenario, domestic appliances are replaced with the equivalent new model at the end of their normal life; in the other scenario, the appliances are given life extensions of 50–100 percent of their normal life, reflecting repair and reuse strategies. The energy consumed during the use phase of each of the products is slightly greater for the reuse scenario, as this scenario foregoes the opportunity to upgrade to a more energy-efficient model. On the other hand, the manufacturing and recycling energy consumed in the reuse scenario is less, as the manufacture of a new product is avoided. In all of the product categories shown, the manufacturing energy saved in the reuse scenario is greater than the use-phase energy saved in the non-reuse scenario. This suggests that for these products, life extension is more energy efficient than replacing the product with the new model at the end of its normal life. However, for most of the products the difference is quite marginal. The main exception is the category of personal computers, where the energy saving from reuse is much more significant, at around 38 percent. This

Figure 62: Total energy consumption of selected household appliances over the period of extended product life (EPL), comparing scenarios in which the products are replaced with new ones at the end of their normal life, with scenarios in which the products are given 50–100 percent life extensions (reuse)



Source: Truttman and Rechberger (2006).

is because the manufacturing energy requirement for personal computers accounts for a much greater proportion of the product's total energy consumption than in the other categories. This makes the result of saving manufacturing energy through reuse a much more decisive overall energy saving.

Tasaki et al. (2013) also explore the energy savings of reusing or extending the lives of household appliances, compared to replacing them with new models. They similarly find that a critical factor is the amount of energy consumed during the use phase, and how this compares to overall life-cycle energy usage. However, the usage patterns of the appliance owner, and the type of model that will be chosen if the product is replaced, are also significant factors. Whereas all of the examples reported by Truttman and Rechberger (2006) show energy benefits of life extensions (albeit marginal in some cases), Tasaki et al. (2013) find some examples where replacing a product at the end of its normal life saves energy compared to life extension. For example, they find that replacing refrigerators after 8–10 years generally results in life-cycle energy savings compared to extending the life of the product, even if the consumer replaces the original with a larger model. This reflects the fact that refrigerators are relatively high and fairly constant energy users, making use-phase energy a high proportion of their life-cycle energy use. As a result, a more energy-efficient model quickly repays energy-saving benefits.

The energy benefits of replacing air-conditioning units and TVs after similar periods was less clear, and depended on the usage patterns of the consumer, and the type and specification of the replacement model. For example, replacing air conditioners did not save energy if the unit was used less frequently than the average, or if it was not replaced with the most energy-efficient new model. TV replacement was also not beneficial if the appliance had low usage, or if the replacement was a larger, more energy-consuming model (Tasaki et al., 2013). In summary, these studies emphasize the importance of life-cycle analyses in understanding the benefits of reuse and life extension, and in informing policy.

Consumers can sometimes lack the incentive to undertake repairs on products, if the cost of carrying out the repairs is greater than the cost of buying an equivalent new product. This resource-inefficient decision merely represents an economically rational calculus based on the relative costs of materials and labour. Repair of electronic products can also be inhibited if the fast-changing performance characteristics of the product cause any particular model to become rapidly obsolete, such that consumer desires, stoked by social pressures, create demand for upgrades rather than life extension. Drivers such as style preferences, product features and technology advances, as well as marketing campaigns, can fuel the perception of technological "obsolescence" and redundancy (Laurenti et al., 2015, Khetriwal and First, 2012). This dynamic is particularly evident for laptops, notebooks and other computing products (Khetriwal and First, 2012, Laurenti et al., 2015). This is particularly interesting given Truttman and Rechberger's (2006) finding that this is one of the product categories in which life extension may yield the greatest energy benefits. Furthermore, the obsolescence of a product may be caused by only one of its components. If this leads to the whole product being discarded, this wastes other parts of the product that still had serviceable lifetimes. Such premature obsolescence across a range of products may be avoided by consciously designing products in a modular fashion, such that new and upgraded components can be added at will, without the need to sacrifice the entire product, most of which is still serviceable (Yang et al., 2014).

2.3.4. Reuse of containers and packaging

Voluntary reuse of containers and packaging at the consumer level can occur given the right structures and a conducive set of incentives or penalties. A modest example is the introduction of small charges for plastic carrier bags, previously

Part III: Increasing resource efficiency: best practices and case studies

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

provided by shops for free, in Scotland, Wales and England. The intention is to encourage consumers to reuse a shopping bag multiple times, rather than taking and immediately disposing of a bag after single use. Also at the consumer level, bottle deposit schemes have been shown to encourage consumers to return bottles to vendors for refilling and reuse. For example, a scheme introduced in 2006 in Estonia achieved a return rate of 89 percent for glass bottles, 87 percent for plastic bottles and 64 percent for metal cans in 2013.[13] Because of the energy costs of recycling both plastic and glass bottles, reusing containers such as drinks bottles considerably reduces their GHG intensity to below that of "one-way" bottles that are sent to recycling after a single use (Simon et al., 2016).

Tasaki et al. (2011) report on the use of refillable shampoo and conditioner bottles in Japan. In 2008 refillable shampoo and conditioner bottles made up around 70 percent of total product sales. Refillable shampoo and conditioner bottles were estimated to have reduced waste by 55 and 53 percent respectively, compared to a counterfactual of no refillable bottles in either market; this is estimated to have saved 10,800 tonnes and 3,900 tonnes of packaging waste for shampoo and conditioner, respectively. The lower cost of refillable bottles is likely to have provided a significant incentive for consumers to take up this option (Tasaki and Yamakawa, 2011).

However, bottle refill schemes can be hampered by the logistical problems in companies recovering their own bottles, given the wide variety of bottle designs on the market. Indeed, such schemes have in the past been subject to legal challenge, on the basis that they create barriers to market entrants (Kromarek, 1990). Deposit return schemes are not only used for refilling: in a variety of countries, including the US, they are used to encourage return of bottles for recycling. However, survey research in the US suggests that if recycling is the intended outcome, municipal recycling programmes such as kerbside collections are more effective than bottle deposit schemes (Campbell et al., 2016, Saphores and Nixon, 2014).

2.4. Recycling materials

Recycling requires the input of energy and other resources to reprocess scrap material into raw material, which can then be used again to make a new product. Such inputs for recycling are typically greater than the inputs required to reuse the materials. As it is therefore a cost that would have been largely avoided had the product been able to reused, or the demand for the product reduced, recycling falls below the other 2Rs in the material hierarchy. However, the energy, resource and environmental impacts of recycling are still typically less than disposal or production from virgin raw material. Nevertheless, this should be confirmed through life-cycle analysis if there is any uncertainty.

Recycling is well established for some sectors and materials, much less so in others. The different rates depend fundamentally on the ease of collecting waste streams, the complexity of pre-processing those streams (where needed) prior to actual recycling, the availability and costs of the technology, and the economic benefits that can be derived from the material once it has been recovered and recycled. Overall, considerably more progress could be made: "Currently… only 25 percent of the 4 billion tonnes of municipal waste produced each year is recovered or recycled. Only 15 percent of all electronic waste is recycled and less than 1 percent of rare earth metals are currently recycled" (UN Environment, 2014b, p. 53).

2.4.1. Recycling of metals

2.4.1.1. Rates of metal recycling

UN Environment (2011d) investigated rates of metal recycling. The data are uncertain due to

13 See http://www.regions4recycling.eu/upload/public/Good-Practices/GP_Tallinn_deposit-packaging.pdf

a variety of factors including lack of available information, and the importance of informal recycling for some base metals and gold, especially in developing countries. However, using a combination of literature review and expert elicitation, recycling rates for 60 metals and metalloids were estimated, as illustrated in Figure 63.

This shows that recycling rates higher than 50 percent were estimated for 18 metals (aluminium, cobalt, chromium, copper, gold, iron, lead, manganese, niobium, nickel, palladium, platinum, rhenium, rhodium, silver, tin, titanium and zinc). Three fell within the 25–50 percent range, and three more within the 10–25 percent range. In the remaining 36 metals, little or no end-of-life recycling occurs.

The higher recycling rates tend to occur in metals that are used in large amounts in easily recoverable applications. For example, steel from cars is a large and relatively easily recoverable stream, leading to the high estimated recycling rates for iron (Fe) and most of the other ferrous metals that are used in the manufacture of steel, as well as lead (Pb) from batteries.

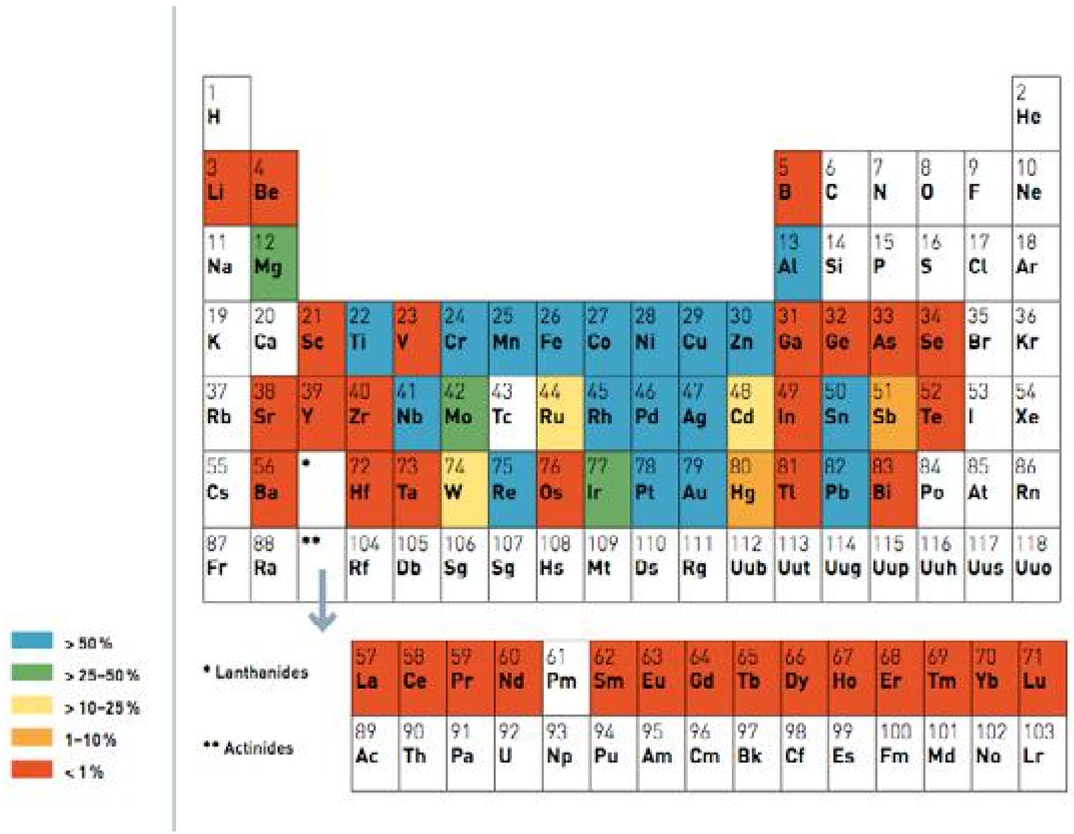
Recycling rates are also high for materials with intrinsically high value — such as gold (Au) and platinum (Pt) — which acts as a strong economic driver to retain the material. On the other hand, where metals are used in small quantities in complex products, and their intrinsic value is not quite as high, recycling rates are much lower: for example tantalum (Ta), which is used in electronics.

2.4.1.2. Opportunities for metal recycling

Recycling rates vary greatly between countries for administrative, economic and technical reasons. For some countries, lack of access to and cost of technologies pose a barrier. Recycling rates also vary between materials, largely driven by their value and the convenience with which they can be accessed from waste streams. Recycling rates of some bulk metals such as iron, zinc, copper and aluminium are already high (60 to 90 percent), and rates for precious metals such as gold, silver and platinum are also quite high (50 to 70 percent) (UN Environment, 2015c).

Metal recycling has significant potential for reducing indirect emissions and resource use.

Figure 63: A periodic table showing global average end-of-life (post-consumer) functional recycling rates (EOL-RR) for 60 metals



Note: Functional recycling is recycling in which the physical and chemical properties that made the material desirable in the first place are retained for subsequent use. Unfilled boxes indicate that no data or estimates are available, or that the element was not addressed as Part of the study. These evaluations do not consider metal emissions from coal power plants.

Source: UNEP (2011d).

For example, primary metals production is responsible for 7–8 percent of total global energy use, as well as for some severe local environmental impacts. Recycling of bulk metals has significant energy benefits compared with production from extracted raw materials: steel, copper, and aluminium recycling can reduce energy used for primary metal production by 60–75 percent, 84–88 percent, and 90–97 percent, respectively (UN Environment, 2013b, p. 86). However, according to a study by UN Environment (2011d), less than one third of some 60 metals studied have an end-of-life recycling rate above 50 percent, and 34 elements are below 1 percent recycling from end-of-life products. Speciality metals such as lithium, gallium, germanium, indium and tellurium are among those with lower recycling rates. They are typically used in very small quantities in individual products, whose design often does not facilitate disassembly for recycling, or are too difficult to handle at low cost (e.g. lithium in batteries). Furthermore, without the inherent value of precious metals, there is insufficient economic incentive to collect, extract and recycle them. Increases in the recycling rates of such metals may be facilitated if products were designed with a view to their disassembly and recycling at the end of their lives. Recycling of speciality metals may become increasingly important as a number of such metals are key constituents of low-carbon technologies such as solar PV cells, wind turbines and batteries.

There may also be physical limits to recycling. For example, it is harder to control the alloy content in steel recycling than in primary production. Higher-grade applications (such as high-strength steel) require precisely controlled alloying, which is not yet possible when refining molten scrap (Allwood, 2014). This means that advanced steel-based alloys, such as high-strength, low-alloy steel, cannot be recycled to the same specifications as the original material: they can only be down-cycled to lower specifications. On the other hand, aluminium can be recycled repeatedly without loss of properties, if non-contaminated. Aluminium has high value, and industry currently recycles all aluminium it collects, without subsidy. Global aluminium recycling rates are about 90 percent for transport and construction appliances, and 60 percent for beverage cans (UN Environment, 2013c). This could be increased through improved logistics and greater participation of authorities and communities.

Electronic and electrical equipment (EEE) contains a wide range of metals and other materials. Waste electrical and electronic equipment (WEEE) volumes are currently between 20 million and 50 million tonnes per year, and are expected to be one of the fastest growing waste streams, as rising GDP drives up consumption of electrical and electronic goods (UN Environment, 2013c). Small WEEE (mobile phones, portable audio devices, etc.) typically has higher concentrations of high-value metals such as gold, silver and palladium than an average-grade natural ore.

Significant barriers to the recycling of consumer electrical and electronic devices can include the inconvenience to consumers of sorting and returning items, as well as the lack of knowledge as to where to take different items, and the lack of incentive for consumers to do so. Consumers are typically not rewarded for keeping materials within a recycling loop, nor penalized for failing to do so — despite the fact that such materials often have value and contain rare metals.

The UK retailer Argos has developed an appliance trade-in scheme, in partnership with the Waste and Resources Action Programme (WRAP), which operates as the lead partner within REBus, a European LIFE+ funded project (REBus, 2016). Following an initial pilot in 10 stores, consumers are now able to take unwanted electrical goods (initially mobile phones and tablets, but with the potential to scale up to other goods) into any of the 788 Argos stores across the UK. The item is assessed and a quote given; if the consumer accepts the quote, this will be reimbursed to them in the form of an Argos store voucher. The item is then sent to an IT asset management company (ITAM), which in the first instance aims to refurbish it for reuse. If this is not possible, the item is dismantled and the parts sent for recycling (WRAP, 2015a, WRAP, 2015b).

The scheme provides consumers with an incentive to return unwanted material goods, as well as convenient locations to do so. The store and ITAM can also benefit from the value of the reclaimed materials, while Argos is also able to increase customer loyalty, as well as its environmental credentials, which are reportedly of increasing interest to consumers. The support that Argos received from WRAP through REBus encouraged the store to consider systems, supply chain logistics and staff training requirements. The scheme has great potential, with WRAP estimating that about GBP£1 billion worth of electrical and electronic goods are sitting unused in UK homes (WRAP, 2015a, WRAP, 2015b).

As well as WEEE, high-value materials are present in a range of products, such as catalysts, batteries and solar cells. However, it is not always economic to recover such metals due to lack of collection infrastructure, and the low value of the small concentrations within any individual

Part III: Increasing resource efficiency: best practices and case studies

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

product, compared with the cost of recycling. For example, catalysts may contain high-value platinum-group metals or rare earth elements. However, recycling rates can be low in countries without appropriate collection infrastructure or where running a catalyst recycling plant cannot be justified due to low volumes (UN Environment, 2013c). An economic challenge therefore is that volumes of minor elements in products are too small to justify dedicated recycling streams. "The processing of recyclate streams currently mostly occurs on the back of large-scale production of base metals with compatible thermodynamic properties, i.e. carrier metals such as copper, iron, lead, lithium, nickel, rare earths (oxides), tin, titanium and zinc" (UN Environment, 2013c, p. 118). Examples of multiple metal extraction are available in copper recycling streams. An integrated copper smelter, using different furnace types, can accept a wide range of copper scrap, from high to low grade. Further, a hydrometallurgical process can extract valuable elements such as bismuth, gold, silver and platinum-group metals. "Therefore, WEEE PGM, metal containing catalysts and other complex recycled materials are often recycled on the back of copper metallurgy" ((UN Environment, 2013c) p. 112).

Metals can be found in less conventional places; for example, landfill mining can be a profitable source of materials ((UN Environment, 2013c), p. 77), and metals can also be recovered from residues of industrial processes ((UN Environment, 2013c), Part I - Section 2.2).

2.4.1.3. Future scarcity of metals

The EU, Japan and the US have produced lists of critical, including potentially scarce, metals. In the future, increasing demands for clean energy technologies may create different kinds of criticalities in metal supply. For example, the production of batteries may expand hugely due to electric vehicles and other electricity storage needs. The main material concerns for these batteries essentially relate to lithium and cobalt. At present, cobalt has the clearest scarcity concerns. As its substitution by less-scarce nickel and manganese reduces performance, three of the six main types of lithium-ion batteries continue to use cobalt (Battery University, 2016). Meanwhile, lithium has no foreseeable substitute, and its resources are highly concentrated in just a handful of countries: Chile, Bolivia and Argentina. Safeguarding such resources and stimulating their recovery and recycling will be crucial enabling factors in the transition to a sustainable economy (UN Environment, 2013c, p. 82, Christmann et al., 2015).

2.4.1.4. Other benefits of metal recycling

The European Environment Agency has suggested that due to the added number of sorting, dismantling and processing activities in a recycling supply chain compared with landfilling or incineration, recycling offers large potential for job creation (EEA, 2011a). Overall employment relating to recycling in European countries increased by 45 percent between 2000 and 2007 (UN Environment, 2013c, p. 83). Recycling of metals can also be expected to alleviate some of the adverse environmental pressures from the use and production of metals, as well as the sometimes harmful residues being released into the environment (UN Environment, 2013b).

2.4.1.5. Limiting factors and barriers for metal recycling

The successful collection of waste streams is a vital prerequisite for recycling. This can involve complicated logistics with multiple stakeholders and materials, and relies on consumer awareness and participation. There are physical limits that prevent fully "closed loop recycling", as there will always be some loss of material due to imperfections, thermodynamics, or human error.

Another important issue is the incomplete or imperfect liberation of materials within a product. This depends greatly on how they were joined in the original manufacture. Bolting or riveting allows higher liberation than, for example, gluing or coating (UN Environment, 2013c, p. 99).

UN Environment (2011d) lists barriers to recycling, especially for metals in consumer goods such as cars, electronics and small appliances, as:

- Product designs that make disassembly and material separation difficult or impossible
- High mobility of products — multiple changes of ownership and global supply chains
- Low awareness about resource issues and missing economic incentives due to low intrinsic value per unit
- Lack of appropriate recycling infrastructure for end-of-life management of complex products, in both developing and developed countries
- Recycling technologies and facilities that have not kept pace with complex and elementally diverse modern products

UN Environment (2013c, Sections 1.7 and 1.8) further emphasizes that material complexity (e.g. use of multiple elements to make alloys) and product complexity (combination of many different materials, some in very small quantities, to make up products) provide challenges to recycling. A further potential challenge facing metal recycling is the time lag created by product lifetimes. By the time appliances reach the end of their life, there is the possibility that technologies may have evolved, rendering the trace metals contained within them no longer useful.

2.4.1.6. Infrastructure and other conditions for optimizing recycling

Recycling requires a technical infrastructure that involves equipment for collection, pre-processing (including dismantling and sorting) and processing (including systemic product-centric approaches). Beyond technology, it also requires an appropriate "stakeholder infrastructure" — to include product designers, consumers, public infrastructure planners, industrial investors or plant operators — with an appropriate "cognitive infrastructure". A comprehensive recycling system is not possible with a purely "material-centric" approach, which sees recycling processes as streams for extracting one particular (usually bulk) metal, regarding other materials as a hindrance. Rather a "product-centric" approach is required, which considers all elements within a product simultaneously, seeing the value in each and optimizing the various relevant recycling processes. Such a "product-centric" approach is therefore "a form of systems thinking" (UN Environment, 2013c) and is necessary to achieving high material-recovery rates.

Another requirement for high recycling rates is clear definitions of what constitutes waste, when waste may again become non-waste materials suitable for recycling, and what the quality of these secondary materials is. This is linked to issues surrounding the calculation of recycling rates and to definitions and clarity of key policy approaches such as "extended producer responsibility", whereby producers are deemed to have some responsibility for the "post-consumer stage of a product's life cycle" (OECD, 2001). Several of the proposals in the Action Plan of the European Commission's Circular Economy Strategy (EC, 2015a) seek to clarify when secondary raw materials should no longer be considered as waste, to develop EU-wide standards for the quality of secondary raw materials, to address key issues relating to the calculation of recycling rates, and to make extended producer responsibility (EPR) schemes more transparent and cost-effective. Another vital issue lies in product design, with "design for recycling" (UN Environment, 2013c, p. 146). This implies that product designers should be encouraged to consider the complexity of recycling, and wherever possible to make design choices that help rather than hinder recycling processes. This includes avoiding incompatible metal mixtures or joints that hinder recycling (UN Environment, 2013c, p. 25).

2.4.2. Recycling of other materials

Many of the considerations that apply to metal recycling apply to the recycling of other products, although obviously to different degrees depending on the product. For example, paper and cardboard recycling also produces environmental benefits over incineration or landfill options (Villanuevaa and Wenzel, 2007), as does recycling of plastic packaging waste (Arena et al., 2003).

Many developed countries have introduced recycling systems for packaging waste, end-of-life home appliances and vehicles, and food waste. These recycling schemes have often helped reduce energy consumption and related primary resources, with incentives able to play an important role in recycling practices. For example, in the 1990s the great majority of UK waste was sent to landfill, because this was the cheapest mode of waste disposal, after accounting for the costs of collection and infrastructure for recycling. In 1996, the UK introduced a landfill tax for non-inert waste at the rate of GBP£7 per tonne, which increased steadily in the following years, reaching GBP£82 per tonne in 2015. Recycling rates in the UK have also increased greatly, reaching nearly 45 percent for household waste in 2014,[14] while 26 percent of the UK's overall waste was landfilled in 2012.[15] While other policies will certainly have contributed to this major change in waste management practices, the landfill tax is likely to have played a very significant role in providing incentives for waste and resource management companies to invest in the necessary recycling infrastructure to provide an economically viable alternative to disposal to landfill.

Zero Waste Europe reports on two case studies from different regions of Northern Italy. In the town of Capannori and the city of Treviso, rates of domestic waste segregation for recycling now exceed 80 percent. In both areas, residents segregate their recyclable waste into multiple streams. They are incentivized by "pay as you throw" systems, under which they are charged according to the weight of non-recyclable waste. Incentives are also provided in both municipalities to encourage composting. Transparency and communication are also important to the schemes' success. In Capannori, residents were extensively consulted and provided with information prior to the introduction of the measures, while in Treviso an online database allows residents to track what waste has been collected from them and to understand how their charges have been calculated (Van Vliet, 2013, Simon, 2015).

Some businesses go to great length to increase their recycling. For example, the Netherlands-based carpet maker Desso set a target to make all its products 100 percent recyclable, simultaneously launching a scheme for collecting its and its competitors' carpets for recycling. Its goal is to use 100 percent materials that can constantly be recycled by 2020. This has required re-engineering the supply chain, design changes and materials substitution (UN Environment, 2014b, p. 53).

Not all recycling is environmentally beneficial, and the extent to which it is needs to be determined through life-cycle analysis. For example, while it is theoretically possible to recycle cement, doing so would require as much energy, and the product would be of lower quality, as newly produced cement. Concrete can be crushed to provide aggregate for construction; however, again, problems may arise if the resulting aggregate is not of comparable quality to aggregate produced by other means. Plastics can readily be recycled but only if the material is of consistent composition. The variety of plastics in use could work against this. For glass, energy use for recycling is similar to energy use for virgin production (Allwood, 2014).

Understanding the limits of recycling therefore requires "detailed knowledge and understanding

14 https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/496508/Digest_waste_resource_2016_v2.pdf

15 https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/593040/UK_statsonwaste_statsnotice_Dec2016_FINALv2_2.pdf

of recycling and high-temperature processing technology, as well as the effects of product design and possible changes in products and consumer behavior. A robust system design will help maximize resource efficiency, for example, reducing landfill usage, while securing the long-term supply of metals for products in the renewable-energy and other sustainability sectors. Ultimately, resource efficiency is determined by how well the links among products, end-of-life processing, recyclate quality, recycling, and metallurgical technology are understood and optimized and, thence, how much material eventually lands in landfill because its complex composition eliminates its economic value… Although the second law of thermodynamics imposes limits on recyclability, such failures also result from avoidable mistakes such as inadequate product design, collection systems, and process optimization" (Reuter and van Schaik, 2012, p. 347).

A European project, Regions for Recycling, has compiled an extensive list of "good practices", mainly for recycling (the Estonian deposit-refund scheme cited earlier is strictly reuse) across the European continent.[16] Many of the good practices concern collection systems (for example, of bio-waste, WEEE, batteries and hazardous waste, selective door-to-door collection), while other practices cover legal and economic instruments, and communication and advisory initiatives.

Two of the case studies illustrate the power of the EPR principle. One shows the results achieved by the Sofia Municipality in Bulgaria, which introduced a requirement for producers of electrical equipment to finance the separate collection from households of WEEE. Two organizations were set up to implement this requirement, and between 2009 and 2013, thanks partly to a vigorous information campaign, the amount of WEEE recovered increased from 722 tonnes to 1,831 tonnes.[17] In another example, the municipality of Ilfov in Romania requires all consumers to pay a "green stamp" when they purchase electrical and electronic equipment (EUR1–6 for large equipment, less for small equipment) which goes to finance the two producer responsibility organizations that "buy back" or just collect WEEE. Through such initiatives, buy-back campaigns now recover about 30 percent of total WEEE sales in Romania, and raw material recovery is 80-90 percent in total.[18]

2.4.3. Industrial symbiosis

The classic definition of industrial symbiosis comes from Chertow (2000, p. 313): "[I] ndustrial symbiosis engages traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water and by-products. The keys to industrial symbiosis are collaboration and the synergistic possibilities offered by geographic proximity." Kalundborg in Denmark is considered the paradigmatic model of a geographically specific industrial symbiosis network (Jacobsen, 2006). Lombardi and Laybourn (2012, pp. 31–32) subsequently described industrial symbiosis (IS) more in terms of the knowledge-sharing and culture change that can arise from a network of industrial actors: "IS engages diverse organizations in a network to foster eco-innovation and long-term culture change. Creating and sharing knowledge through the network yields mutually profitable transactions for novel sourcing of required inputs, value-added destinations for non-product outputs, and improved business and technical processes." Whereas an IS concept based around physical exchanges of materials and energy would likely require close geographical proximity of the industries involved, Lombardi and Laybourn's emphasis on knowledge-sharing, innovation

16 See http://www.regions4recycling.eu/R4R_toolkit/R4R_good_practices

17 See http://www.regions4recycling.eu/upload/public/Good-Practices/GP_Sofia_WEEE-collection.pdf

18 See http://www.regions4recycling.eu/upload/public/Good-Practices/GP_Ilfov_WEEE.pdf

and culture change opens up the possibility of a version of IS that is less dependent on close geographical proximity. Both physical exchanges and knowledge-sharing can be important aspects of industrial symbiosis, and are by no means mutually exclusive.

There are numerous case studies of successful applications of industrial symbiosis, through the work of the National Industrial Symbiosis Programme (NISP), which was pioneered in the UK but has now been replicated across 25 countries. For example, the NISP website states that: "Arla Foods, one of the UK's leading dairy producers, uses substantial volumes of water on a daily basis for washing equipment, which subsequently becomes contaminated and not fit for much. Instead of simply flushing it down the drain, Arla looked at the issue and (with the help of NISP) was able to redirect the contaminated water to a nearby Severn Trent Water biogas plant where it is used as a 'new' input into the production process – industrial symbiosis in practice. Elsewhere a nitrogen producer in the North East of England captures steam and CO_2 generated as by-products of its manufacturing process. The steam is channelled to power a nearby vegetable plant and the CO_2 reassigned and used to support the growth of fruits and vegetables within the plant. This particular example has inspired a number of similar projects as far afield as the United States and Canada.

"Unlocking the value embedded in under-utilised industrial resources can sometimes be challenging. The process often involves more than merely brokering a link between two or more companies. Indeed many industrial symbiosis links or transactions are more complex than a simple exchange of resources. In many cases a 'used' resource requires some sort of treatment to make it fit for a new purpose. This may involve some sort of extraction process, shredding or other treatment. In practice using industrial symbiosis as an approach to commercial operations — using, recovering and redirecting resources for reuse — results in resources remaining in productive use in the economy for longer. This in turn creates business opportunities, reduces demands on the earth's resources, and provides a stepping-stone towards creating a circular economy."[19]

Table 8 shows the results of the NISP programme over five years (2005–10), during which time the UK Government invested GBP£27.7 million in NISP. The Value-for-money column shows that NISP was not only able to achieve environmental results extremely cost effectively, but actually generated and saved money. Compared to the government investment of GBP£27.7 million, around five times as much was leveraged in private investment, 10 times as much was generated in extra sales, 10 times as much saved in business costs, and three times as much returned to the UK Treasury.

The industrial symbiosis concept was also at the heart of the Japanese Eco-Town Programme, which established 26 eco-towns across Japan. The aim of this government-led programme was to reduce the high levels of waste going to landfill sites and to regenerate local industries. As such, a key strategy was the conversion of waste from one industrial process into a valuable input for another (Van Berkel et al., 2009).

For example, the Kawasaki eco-town "aims primarily for effective utilisation of residential, commercial and industrial wastes generated in the city and recycling these into raw materials that can be used by industries located in the city (e.g. cement and iron and steel works)" (Van Berkel et al., 2009). Specific examples of recycling activities in Kawasaki are recycling of plastic as a reductant for blast furnaces, for concrete

19 See NISP 2009. The Pathway to a Low Carbon Sustainable Economy. Birmingham: National Industrial Symbiosis Programme, International Synergies and http://www.nispnetwork.com/media-centre/case-studies

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

Table 8: Environmental and economic benefits from NISP, April 2005–March 2010

	Actual year-on-year[1]	Cumulative over 5 years[2]	Value for money (Public investment/ unit output)[3]
Environmental benefits			
Landfill diverted (Mt)	7.0	12.6	0.44 (£/t)
CO_2 reduction (Mt)	6.0	10.8	0.51 (£/t)
Virgin materials saved (Mt)	9.7	17.5	0.32 (£/t)
Hazardous materials reduced (Mt)	0.36	0.7	7.9 (£/t)
Water saved (Mt)	9.6	17.2	0.32 (£/t)
Economic benefits			
Extra sales (£m)	176	317	0.087 (£/£)
Costs saved (£m)	156	281	0.099 (£/£)
Extra Government revenue (£m)		89	0.31 (£/£) Fiscal multiplier: 3.2 (£/£)
Private investment (£m)	131		
Jobs created	3683		
Jobs saved	5087		

Source: Author calculation from data in NISP, 2009, p. 5.

[1] Total over 5 years computed by simply summing the results for each year (independently verified data April 2005 to September 2009, estimate based on project pipeline September 2009 to March 2010).
[2] Total over 5 years assuming NISP contribution to savings of only 60 percent, but persistence of savings to subsequent years, declining by 20 percent per year.
[3] Public investment of £27.7m over five years. For environmental categories, this is assumed to be split equally between 5 categories (i.e. £5.5m per category), divided by results in Cumulative column; for economic categories, the full public investment figure (i.e. £27.7m) is used as the numerator.

formwork and for ammonia production; as well as paper recycling and PET-to-PET plastic recycling. In addition to reducing material waste, it is estimated that the industrial symbiosis strategy in Kawasaki reduced life-cycle carbon emissions by 13.77 percent, mainly from iron and steel, cement and paper manufacture (Dong et al., 2014).

As a result of government subsidies, 61 recycling facilities have been established across the 26 eco-towns, with a combined capacity of nearly 2 million tonnes of waste per year. However, Van Berkel et al. (2009) find that for every government-subsidized recycling plant, a further 1.5 unsubsidized plants were built by the private sector. This suggests that government actions to establish an industrial symbiosis "ecosystem" can act as a springboard for further private sector-led development of environmental industries.

Industrial symbiosis is also well established in other Asian countries. In the case of China, Yu et al. (2014) report on the Xinfa group of industries, a cluster of various process plants with aluminium production at its core. The cluster has established 11 industrial symbiosis links, including: coal ash from power plants used to make bricks; carbide slag used as a substitute for slaked lime in alumina production; carbon monoxide off-gas from the calcium carbide factory burned for energy; and red mud from alumina production reused as a building material. These measures have been estimated to reduce carbon emissions by 11 percent (Yu et al., 2014, Yu et al., 2015c). In another eco-industrial park, the Rizhao Economic Technological Development Area (REDA), the industries include cereal oil and food, machinery, pulp and paper, textiles and brewing. During 2011, 31 material exchanges between different enterprises were established, including: 71,446 tonnes of white sludge from the pulp and paper factory used instead of calcium carbonate in citric acid factory and cement factories; more than 66,000 tonnes of fly ash and more than 20,000 tonnes of green mud used to produce cement and new building materials; more than 19,000 tonnes of wood chips used to produce wood charcoal; 27,000 tonnes of sludge, 2,250 tonnes of seaweed slag, 7,400 tonnes of vinasse, and 1,900 tonnes of waste clay used to produce organic fertilizer; and 85 tonnes of metal scraps retrieved by smelting plants. Most of the exchanges arose through government promotion, but three occurred spontaneously (Yu et al., 2015b).

Park et al. (2016) report on the first phase of the Eco-Industrial Park (EIP) programme in Korea, from 2005 to 2010: the projects involved product, energy and water reuse between industries. They calculate that the 47 projects reduced material waste by 477,633 tonnes, as well as saving energy, and reducing emissions and wastewater. The projects also reduced costs by around US$97 million through energy and material savings, and generated US$92 million of revenue from selling by-products. The authors observe that projects to generate revenue from by-products tend to have a higher rate of return than projects to generate savings from material and energy efficiencies, due to the larger upfront investment typically required in the latter case (Park et al., 2016).

Another example of an industrial cluster is the Textile Recycling Valley initiative in Northern France, which aims to increase the collection and reuse of textiles. This voluntary collaboration of five core partners aims to capture and reuse 50 percent of the region's waste fabric by 2019 (EMF, 2016a). Meanwhile, Golev et al. (2014) report on an industrial symbiosis cluster in Gladstone, Australia. The area includes alumina refineries, an aluminium smelter, a cement plant and an ammonium nitrate and sodium cyanide producer, among other industries. The main existing resource exchanges include: secondary treated water effluent from the sewage treatment plant transported via an 8.5 km pipeline and reused for red-mud washing operations; fly ash from a power station reused as a cement additive; spent cell linings, or calcined ash, and solvent-based fuels, reused as fuel and raw material in clinker production; and by-products of ammonium nitrate production supplied as fertilizer for agricultural companies. Due to an expected future growth of industries in the Gladstone industrial area, the authors project that by 2020 there could be a fourfold increase in solid waste, a doubling of freshwater consumption and a threefold increase in CO_2 emissions, compared with 2011 levels. However, the authors' analysis suggests that continuing to develop symbiotic resource synergies could help reduce water consumption by 40 percent, solid waste by 20 percent and CO_2 emissions by 5 percent, from the 2020 projected levels (Golev et al., 2014). More examples of industrial symbiosis are discussed in Part III - Section 7.1.3, which uses case studies in China, India and Brazil to explore the potential benefits that eco-industrial parks, or other clusters of industries, can have in improving water-use efficiency.

2.5. Alternative business models

Many of the novel approaches to material efficiency discussed in this section could be assisted by the emergence of new business models. One of the most important, and widely transferrable, is the leasing — or product service system — model. In general terms, rather than a customer buying and owning an individual product, a leasing model involves a customer contracting with a company for the provision of a service. The ongoing contract places a greater incentive on the company to design and provide products that can be operated, maintained or replaced in a more resource-efficient manner.

Examples of leasing models can be seen in car-sharing clubs, building services and office supplies (UNIDO, 2013, WRAP, 2016b). At the industrial scale, chemical leasing is an interesting example, whereby the producer sells the functions performed by the chemicals — such as number of pieces cleaned, or area of products coated — rather than the chemicals themselves. The responsibility of the producer is thus extended "and may include the management of the entire life cycle" of the chemical products (UNIDO, 2013). Erbel (2008) reports on one such project: a collaboration between PERO, an Austrian manufacturer of metal-cleaning machines, and SAFECHEM, a subsidiary of the Dow Chemical Company of Düsseldorf, Germany. These partners were contracted to provide chemical cleaning services to an Austrian manufacturer of car parts, Automobiltechnik Blau. The model allowed the customer to outsource the chemical cleaning activities that were not within its core competencies. The stability of the contract enabled the contractors to invest in high-quality cleaning equipment, which would not normally be chosen in typical market conditions due to their high upfront cost, but which yield longer-term returns. This pilot project was expected to be generating positive returns by its second year. It is estimated that arrangements of this kind can reduce energy use by around 50 percent and solvent use by around 70 percent (Erbel, 2008).

2.6. Conclusions

The previous sections have reviewed a range of potential resource-efficient interventions, across product supply chains, structuring the discussion under the broad banner of "the 3Rs". "The 3Rs" is a memorable high-level summary of a material management hierarchy, and is widely agreed to be an appropriate framing device for setting out resource efficiency priorities in the area of material management. However, it is of course a form of shorthand. Each of the 3Rs should not be thought of as a single activity, but as a broad term encompassing a wide variety of specific activities and interventions, examples of which have been explored in this chapter.

The discussions in this chapter identified a range of options for increasing resource efficiency in material management, as well as some examples of resource efficiency in practice. However, the discussions also showed that the "3Rs" do not inevitably lead to resource-efficient product supply chains. The legacy of past policy decisions and technological, behavioural, organizational and institutional obstacles to innovation in resource efficiency present significant barriers to the 3Rs. Where pre-existing regulations create unintended barriers to implementing the 3Rs, these would of course need to be addressed in order to increase resource efficiency in material management.

An important recurring theme is that the attractiveness of resource efficiency depends on the relative cost of labour and materials. Frequent examples have been seen where the labour cost of implementing a resource-efficient strategy outweighs the cost-saving from the reduced use of materials that the strategy enables, or where the labour cost of repairing an object is greater than that of throwing it away and the cost of the materials in a new one: it is often cheaper to be resource-inefficient. Such resource-inefficient trade-offs occur at the level of the individual consumer, as well as the firm level. It is hard to see how this can be resolved without significant interventions that change the relative prices of labour, secondary and virgin materials, such as perhaps through resource and environmental taxation. Some examples of such interventions have been touched on in this chapter. However, a more detailed analysis of policies and their relative merits is beyond the scope of this report.

Creating the new kinds of infrastructure, physical resource exchanges, as well as knowledge and information exchanges that will be required to enable 3R strategies to deliver more circular resource flows, is an important challenge. For many firms, ensuring a steady supply of cores to remanufacture is a constant concern and an ongoing business challenge, and the lack of an effective collection infrastructure that enables take-back of recyclable and remanufacturable goods is a significant barrier. However, lessons can be learned from a number of successful examples of industrial symbiosis, in which groups of businesses, which can be geographically clustered, achieve synergistic resource flows to their mutual advantage. Such activities frequently see important roles for both private and public sector coordinating actors. They also frequently demonstrate the tremendous untapped potential — in terms of both increased resource efficiency and economic gains — that is available through more integrated industrial activities. The examples in this chapter thus show that while there are important barriers to increasing material efficiency, there are also very significant opportunities.

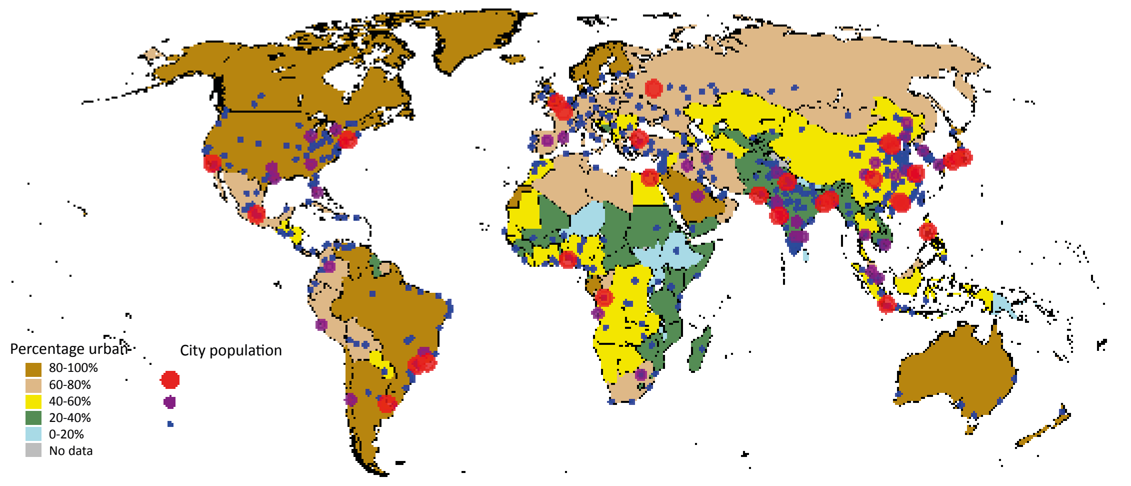
3. RESOURCE-EFFICIENT URBANISM

3.1. Introduction

As major centres of human populations, cities and towns play a major role in the global rate of resource consumption, and are significant sources of anthropogenic environmental impacts. Correspondingly, they are also critically important as sites of potential innovations that may substantially help achieve the SDGs within planetary boundaries by 2050.

In 2014, 54 percent of the global population were estimated to be living in urban areas (UN, 2014). Figure 64 illustrates the distribution of this urban population across the world, showing the percentage of urban population by country, and the location of urban agglomerations by size class.

Figure 64: Percentage urban and urban agglomerations by size class, 2014



Data source: World Urbanization Prospects: The 2014 revision, UN, 2014.

Cities are responsible for around 80 percent of global GDP, and for the consumption of around 70 to 75 percent of global energy and materials (IEA, 2008, Hodson et al., 2012, Shell, 2012, UN Environment, 2013a). Thus, urban expansion is a major cause of loss of agricultural land, groundwater depletion, increasing water pollution and ecosystem destruction. Urban growth is therefore one of the main drivers of food insecurity, water scarcity and ecosystem degradation. A significant portion of the world's poor lives in urban slums, constituting around 30 percent of the total global urban population. With the global urban population expected to increase by about 2.4 billion people up to 2050 (UN, 2014), the critical importance of achieving urban-level decoupling for sustainable development is clear. As the director general of the 1992 Rio Earth Summit, Maurice Strong, remarked, *"The battle to ensure our planet remains a hospitable and sustainable home for the human species will be won or lost in the major urban areas"* (quoted in Girardet, 2004, p. 3).

However, while urban areas are key contributors to unsustainable resource consumption, they are also sites with great potential for resource efficiency and decoupling. As will be discussed with reference to a variety of case studies in Part III - Section 7.4, the spatial concentration of people in cities can potentially enable greater optimization of the infrastructures that provide important services such as health, education, transport and employment (Cervero and Sullivan, 2011). This could enable such services to be provided more efficiently in cities than in less densely populated areas. However, this will depend entirely on how urban infrastructures are configured to connect urban dwellers to the resources they need to enjoy a decent quality of life. Infrastructure is therefore key to urban resource efficiency (Hodson et al., 2012, Ramaswami et al., 2012b, Bulkeley et al., 2014, Muller et al., 2013, UN Environment, 2013a).

Given the projected growth in the global urban population by 2050, it is not only necessary to reconfigure existing urban infrastructure, but also to avoid "business-as-usual" building of new urban infrastructures. As urban infrastructure typically lasts between 25 and 75 years, infrastructure and buildings built today will create a "lock-in" effect to 2050 and beyond, dictating urban metabolic flows for decades to come. If urban infrastructure is designed now in an unsustainable way, this will create a long-term obstacle that will prevent cities and towns from reaching a pathway of sustainable development (UN Environment, 2013).

Urban infrastructure not only embodies materials and energy in its physical stocks, but also conducts the flows of materials and energy through urban areas (Hodson et al., 2012, Muller et al., 2013, UN Environment, 2013a). The design of infrastructure systems for energy, transport, sewage, water, telecommunications, etc., and of buildings, ultimately determines the quantity of materials and energy required for the actual urban fabric (i.e. the stocks), and the amount of material and energy flows that are conducted and wasted (UN Environment, 2013a). Urban resource efficiency must involve considering both of these kinds of energy and material impacts. Infrastructure design can have a substantial effect on the efficiency with which materials and energy flows are conducted through the urban system. The materials and energy embodied in the physical infrastructure and buildings themselves are also of concern — especially the CO_2 emissions that would be emitted through business-as-usual production of the urban fabric required for future urban expansion (Muller et al., 2013, Angel, 2012).

The way in which urban infrastructures and buildings have been designed, built and operated has, to date, relied on technological configurations and governance approaches that assume a limitless supply of resources, and limitless capacities of environmental sinks to absorb their waste (Hodson et al., 2012, p. 790, UN Environment, 2013a). In other words, urban infrastructures and buildings have not been designed and built with sustainability in mind. Given the large proportion of global material consumption for which urban settlements are currently responsible, and the anticipated future growth in urbanization, reconfiguring the world's urban infrastructures would be a crucial step towards achieving global sustainable development (Hodson et al., 2012, UN Environment, 2013a). The extent to which we manage to achieve the SDGs this century will largely be determined by the extent to which we can redesign our urban infrastructures to consume materials and energy far more efficiently, and to preserve and also restore the environmental conditions on which we depend (Birkeland, 2008, UN Environment, 2013a).

3.1.1. The heterogeneity of urban settlements

At the outset, it is important to clarify the range of settlement types that can be included within the concept of urbanization when discussing current statistics and future projections. Urban settlements are highly heterogeneous. Although discussions of urbanization may most readily conjure up images of today's "megacities" — cities with a population of 10 million or more people (Kennedy et al., 2015, UN, 2014) — these kinds of urban settlements are only part of the story.

Cities are diverse because of their different sizes, economic structures, demographics, and proximity to natural resources. These differences require caution when comparing cities and the potential for different resource efficiency strategies within them. Often a few cities that have vibrant economies are able to develop and implement policies that support sustainability and energy efficiency, but these are rarely able to be replicated in large numbers of cities. For example,


Photo: ©UN Habitat/Julius Mwelu

San Francisco and Berkeley have, for many years, implemented a time-of-sale energy conservation ordinance. This requires commercial and residential properties to have basic energy efficiency features at the time of their sale (see summary details in Ramaswami et al., 2012a). These policies are rarely replicable to other cities, as property values in San Francisco have created an excellent real estate market where such policy innovation has been feasible and supported by citizens and realtors alike. Likewise, Kennedy et al. point to Geneva as a low-carbon city (2009) due to its location near abundant hydropower: most cities are not located within such proximity.

The United Nations estimate that around 54 percent of people on the t now live in urban settlements. However, close to half of these urban residents live in settlements of fewer than 500,000 people (UN, 2014). Furthermore, many urban dwellers are in fact urban slum dwellers. It is estimated that in 2014 there were approximately 880 million people living in urban slums – constituting around 30 percent of the global urban population (UN, 2015a). The recent Millennium Development Goals report estimated that in Sub-Saharan Africa nearly 60 percent of the urban population still live in slums (UN, 2015a).

Another important category of urban settlement is that of the "suburb". Suburban sprawl is witnessed in many developed countries (Stanilov and Scheer, 2004). Boundary issues can complicate considering the resource efficiency of such cities, as cities with extended suburbs often have significant spillover effects, and potentially self-selection bias of the people living in them. As an example, consider the recent study of Jones and Kammen (2014), they compute consumption-based emissions of core cities and larger metropolitan areas. They find that any savings in apparent energy intensity in the core city are "evened out" when the whole commuter-shed is considered. Hillman et al. (2011) showed a similar effect in Denver and 25 other US cities: if only traffic within the city boundary is considered, some cities may report lower VMT per capita, but when trip origin and destinations are allocated (50 percent to origin and 50 percent to destination), the apparent efficiency of exemplar cities such as Portland, Seattle and Boulder disappears when regional travel to and from these cities is included (Hillman and Ramaswami, 2010).

The emergence of extended peri-urban periphery zones is also increasingly significant in emerging economies. In the South-East Asian context, the emergence of "extended metropolitan regions" (EMRs) has been observed. These occur when high-tech production spills out of major metropolises and into surrounding areas, attracted by cheaper land. Such areas remain predominantly rural with large areas under cultivation, but also increasing proportions of some households' incomes are derived from non-agricultural activities. However, the provision of services remains less secure than in urban areas, as they do not benefit from the spatial concentration of infrastructures in urban centres (UN Environment, 2013). The emergence of EMRs can be "accompanied by rising incomes and improved quality of life for some inhabitants, but often at the expense of the immiseration of others in both these new cores and peripheries" (Simon et al., 2006).

In Latin America and the Caribbean, another emerging urban form is the poly-centric form, where growth concentrates in hotspots, within a wider metropolitan region. One example is the Monterrey Metropolitan Area in Mexico. Such poly-centric forms allow service provision to be decentralized, but can encounter difficulties when more coordinated approaches would be desirable (UN Environment, 2013a).

Cities are part-consumers and part-producers with large transboundary supply chains and spillover effects (Chavez and Ramaswami, 2013). To fully demonstrate the efficiency of the systemic interventions, it is important to consider transboundary and life-cycle impacts of any infrastructure change, as noted in infrastructure supply chain footprints (Ramaswami et al., 2012a, Chavez and Ramaswami, 2013). The flow of people, resources, waste and pollution between urban and rural areas emphasizes that the boundaries of urban areas are increasingly porous and extended. Rather than attempting to draw strict boundaries around cities, the concept of the peri-urban interface (PUI) may therefore be useful to consider the problems and opportunities involved in the "sustainable development of adjacent rural and urban systems" (UN Environment, 2013a).

3.1.2. Future growth and demographics

With these distinctions in mind, this section goes on to discuss possible future trends in urbanization.

The United Nations World Urbanization Prospects (WUP) report (UN, 2014) projects that continuing population growth and urbanization will result in the global urban population expanding by 2.5 billion people by the middle of the century. The global level of urbanization is expected to rise from 54 percent (in 2014) to 66 percent by 2050 (UN, 2014). Such demographic projections do, of course, entail considerable uncertainties.

The number of very large cities is expected to grow, with the number of megacities expected

Photo: ©AFP

to increase from 28 today to 41 worldwide by 2030. However, the fastest growth in urban population is expected to occur in the villages, towns and small- to medium-sized cities of Africa and Asia (UN, 2014). Indeed, according to the World Economic Forum, this rapid urbanization "will be an almost exclusively non-Western affair: about 94% of those who will move to cities in the next few decades will come from the developing world" (World Economic Forum, 2014, p. 9).

Overall nearly 90 percent of the global urban population increase is set to occur in Africa and Asia, which are currently the two most rural continents in the world, with urbanization levels of 40 and 48 percent respectively (UN, 2014). More specifically, 37 percent of the projected urban population growth to 2050 is expected to come from only three countries: China, India and Nigeria, which are estimated to contribute 404 million, 292 million and 212 million urban dwellers respectively (UN, 2014).

Demographic changes, cultural shifts and increases in income are leading to reduced household sizes in many countries. This trend is expected to continue, with average household sizes falling from 3.2 people to 2.7 people by 2025. This would comparatively reduce the density of housing in cities, causing a faster growth in households – and associated land, materials and energy – than the population growth rate, in many cities (UN Environment, 2013a). In support of this hypothesis Kennedy et al. (2015) have compared megacities across the globe. They find significant correlations between heating and industrial fuel use per capita, and urbanized area per capita; and between electricity use and urbanized area per capita. In particular, the regression of per capita electricity demand against both residential gross floor area per capita and urbanized land area per capita gave a strong correlation ($R2=0.95$). Correlations were also found between water use per capita and urban area per capita, and between waste generation per capita and GDP per capita (GDP per capita itself being relatively strongly correlated with urbanized area per capita). These results suggest that increasing GDP per capita and increasing urban land use per capita (that is, decreasing urban density) may be expected to be associated with increasing per capita consumption of resources and energy.

However, in some tests the authors find examples of residuals that show other factors at play, such as local policy frameworks. For example, in comparing waste production in New York (1.49 tonnes per capita) with London (0.32 tonnes per capita), the authors suggest that the influence of the UK landfill tax may be significant in explaining the difference. Seto et al. (2014) and Kennedy et al. (2015) show that land areas and built areas are increasing at rates that are much higher than the rates of urban population growth. This means that much greater urban efficiencies must be realized to achieve "decoupling", i.e. the urban efficiencies must be much greater than the population increase rates. For example, in fast-growing cities with population growth rates exceeding 7 percent, the population doubles every 10 years. This means that for absolute decoupling, energy use per person must decrease by more than 50 percent in the same 10 year period — a tall order.

Heinonen and Junnila (2011) studied household consumption behaviours, including travel behaviours, in EU cities. They found that while core cities (with greater density and a greater focus on transit) had lower surface travel, such households tended to have higher overall consumption-based emissions. More generally, in countries with a very high urbanization percentage (exceeding 80 percent such as the US, EU and Japan), the trend in per capita consumption (after correction for trade) is that of increasing emissions per capita over the past two decades. Steinberger et al.'s (2012) data suggests that the consumption patterns in aggregate in Japan, the US and EU countries have not decreased as such. It is important to note that consumption-based emissions in Japan are on aggregate much lower than in other highly urbanized nations such as in the US and EU countries — likely because of the premium on land and floor area in Japan.

In developing and emerging economies, income-driven lifestyle changes in cities will also have a major impact. For example, from 2000–2010, the share of cars that were sold in emerging market cities grew from 8 percent to 37 percent (BCG, 2010). It is estimated that India's urban consumption could increase sixfold between 2005 and 2025, and sevenfold in China (MGI, 2011). At the same time, growing numbers of urban poor and urban slum dwellers, as well as rising inequalities, are expected to be critical issues for emerging market cities (UN Environment, 2013a).

Economic structure also affects the development of cities. In a study of Chinese cites, Ramaswami et al. (2016) have shown that GDP-population scaling differs between different city types by economic structure. Specifically, GDP-population scaling is sublinear in highly industrial Chinese cities, and super-linear in the others. Further, the data showed that household electricity use scales linearly with population, as expected (with high r sq > 0.85), while commercial-industrial electricity use scales linearly with city GDP.

By contrast, some cities in developed countries are starting to show stabilizing or even negative growth. In some cases, deindustrialization creates "shrinking" cities with over-capacity and redundant infrastructure (UN Environment, 2013a).

3.2. Cities as "urban metabolisms"

Since the 1990s, a growing body of research has emerged that conceptualizes urban systems as urban metabolisms, i.e. systems that conduct flows of resources into, through and out of urban systems. Figure 65 shows an early representation of this provided by Girardet (1992).

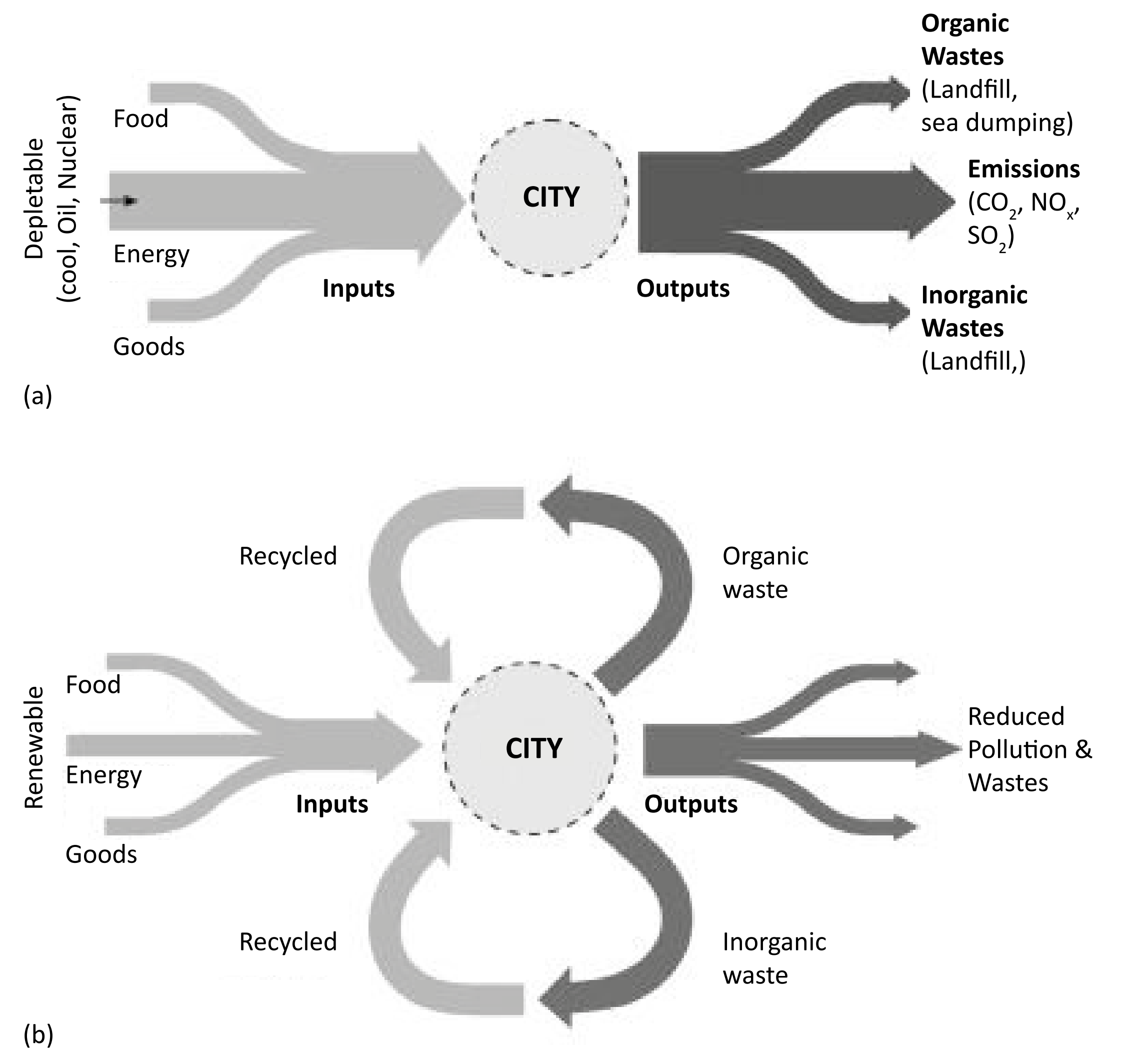
Figure 65 (a) represents an urban metabolism supplied by large quantities of food, energy and material inputs, and releasing large quantities of outputs, in the form of waste and emissions. Figure 65 (b) represents an urban metabolism which is able to use its inputs more efficiently, through recycling both organic and inorganic materials. This reduces the quantity of inputs required, and outputs produced, and by extension the overall flow of energy and materials through the system.

The difference between a highly linear and resource-inefficient urban system, and more "circular", resource-efficient urbanization, lies in the decisions and actions of the various social actors that live and operate within that system, the institutions and practices they create, and the infrastructures that are developed as a result. Ramaswami et al. (2012b) build on the foundation of the urban metabolism concept, to develop the "social-ecological-infrastructural systems" (SEIS) framework (Figure 66). They argue that:

> "… social actors are the primary agents of change, and institutions are the instruments through which actors shape the current and future trajectory of urban infrastructures in terms of resource use, pollution, climate risks, and health impacts. Any study of resource-efficient, environmentally sustainable, and healthy cities must necessarily incorporate transboundary infrastructures serving cities, along with associated cross-scale social actors and institutions that govern these infrastructures" (Ramaswami et al., 2012b, p. 802).

As shown in Figure 66, the SEIS framework identifies three clusters of societal actors that shape the urban system: infrastructure designers and operators (who derive designs and systems directly from idealized visions of how urban systems should work); policy actors (that set the regulatory and land-use frameworks for resource use within specific infrastructure configurations); and "individual users" who are the primary resource users and effectively "buy into" the applied visions of the designers (home dwellers, businesses and facilities). The values, habits and culturally mediated practices of the individual

Figure 65: Cities as "urban metabolisms"

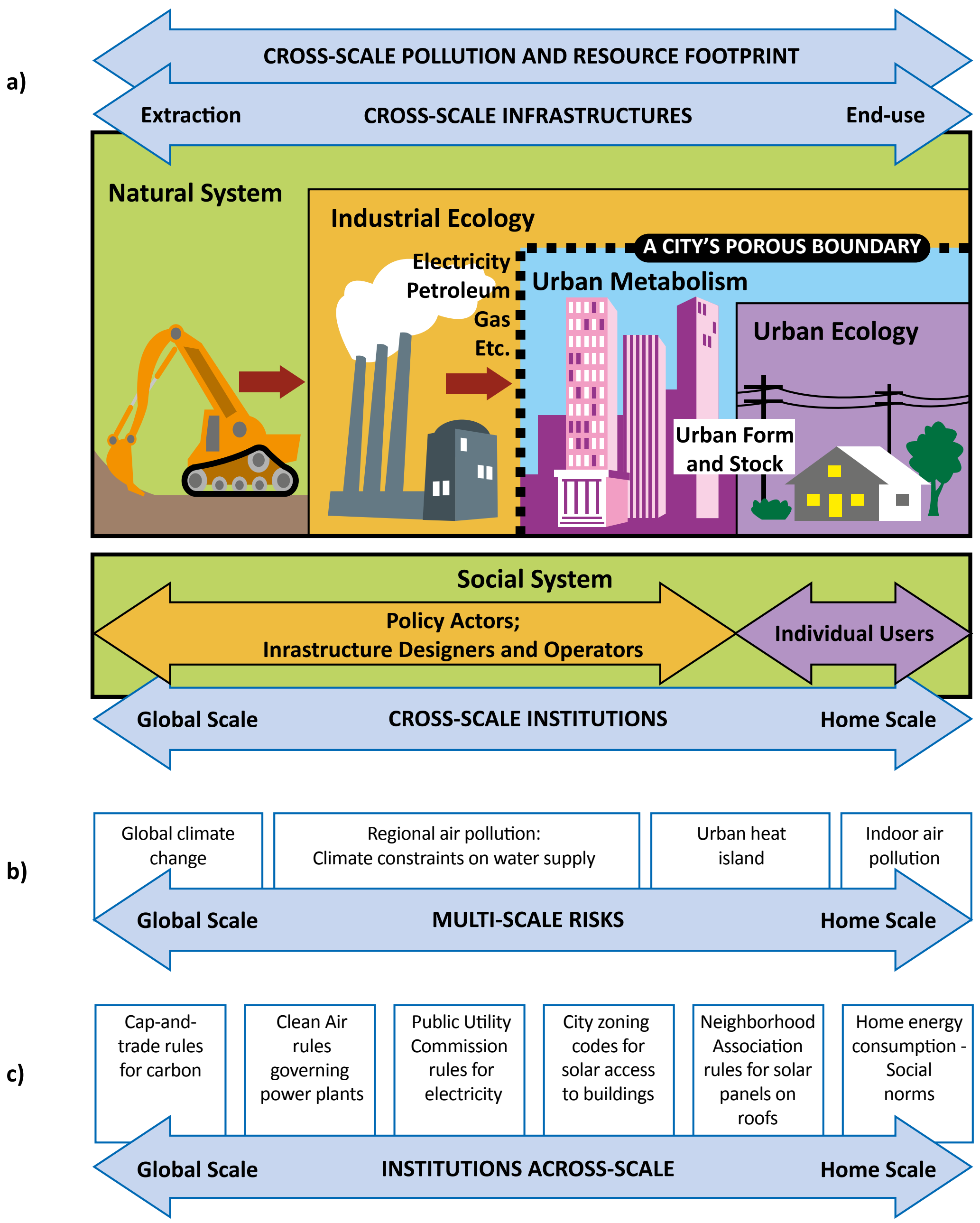


users are formed by the urban infrastructures in which they find themselves; but these values and practices also contribute to shaping the way individuals use the urban landscape, and indeed to forming that urban landscape itself. Thus, Thomas Hughes' description of large technological systems as "both socially constructed and society shaping" (1987) also applies to urban systems. The SEIS concept also emphasizes that the urban metabolism of a city is embedded within wider resource flows mediated by transboundary infrastructures, and nested within wider global, national, regional and local regulatory regimes and their respective societal actors (as discussed in Part II - Chapter 4). The emergent outcome is what can usefully be called urbanism: the specific configuration of infrastructures, flows and ways of urban living in a particular city.

3.3. Practices and approaches

There are three key types of intervention which promote resource-efficient urbanism: spatial restructuring of the urban morphology to reverse the century-long trend towards de-densification; transit-oriented development (TOD) to subvert the private car and drive urban

Figure 66: Illustration of the social-ecological-infrastructural systems (SEIS) framework



Pictorial illustration of the social-ecological-infrastructural systems (SEIS) framework depicting: (a) integration across the spatial scale of infrastructures, urban metabolism, industrial ecology, and urban resource/pollution footprints with social actors and institutions; (b) multiple and multiscale risks posed to cities by infrastructure–environment interactions across scales; (c) select examples of institutions that shape energy use and greenhouse gas (GHG) emissions across scales.

Source: Ramaswami et al., 2012b.

regeneration; and efficient and renewable energy systems (ERES). All three require entrepreneurial modes of governance capable of directing urban experiments towards comprehensive urban transitions. The primary significance of urban morphology, TOD and ERES interventions is that they are, on the whole, controllable by local governments.

3.3.1. Urban morphology

According to Serge Salat and Loeiz Bourdic from the Urban Morphology Laboratory at CSTB, Paris, it is possible to radically improve "urban productivity" by a factor of at least 10 and possibly even 20 (Salat, 2011, Salat and Bourdic, 2011). They argue that to face the challenge of climate change, "the design of cities constitutes the greatest potential source of savings at zero or negative cost. Denser, better connected cities designed to be more open to the light, sun and wind will improve well-being along with social and economic exchanges while economizing all the square kilometres of asphalt, the concrete, the electricity and the water that are currently lost in the overly long, overly scattered and overly disseminated networks of our sprawling contemporary cities. If the productivity of the urban system was multiplied by ten, humankind could continue to urbanize, creating wealth and eliminating poverty while halving the pressure exerted on the planet" (Salat and Bourdic, 2011).

The substantial body of quantitative work by Salat and colleagues has demonstrated that it is, indeed, possible to radically improve "urban productivity" (essentially the same thing as "resource-efficient urbanism"). This can be achieved through four systemically interrelated interventions: spatial restructuring of the urban morphology to achieve much greater densities — and a richer mix — of housing, jobs and amenities at the neighbourhood level; human-scale sustainable design to create the conditions for "soft" mobility (pedestrianization, cycling) at the city and neighbourhood scales and "passive" heating, cooling and lighting at the building level; sustainable energy (radical resource efficiency of all components such as vehicles, infrastructures, buildings and factories, plus maximum use of renewable energy) at all scales (city-wide, neighbourhood and building); and the promotion of sustainable behaviours (e.g. desire to recycle waste, use public transport, walk, cycle, grow food and use parks).

The actual improvements in energy and resource productivity of each of these interventions are not simply the sum of each intervention, but are "multiplicative" if they are implemented in mutually reinforcing ways. The evidence shows that if the urban form is dense enough and correctly oriented (for shade, sunshine, light, wind, ventilation), energy consumption would be reduced by a factor of two; if buildings are ecologically designed to be as resource-efficient as possible, reductions by a factor of 2.5 would be achieved; if renewable energy accounted for approximately 20 percent of total consumption, another factor of two saving would be realized; and if human behaviours were motivated by a desire to live sustainably, this would also reduce energy demand by a factor of two. Using the multiplicative method, this would result in an overall reduction in energy use by a factor of 20, significantly exceeding the factor of four or even factor of 10 target that is usually referred to (Weizsäcker et al., 2009).

The same kind of analysis can be used to analyse transportation: a transit-oriented morphology, soft/passive transits (pedestrianization/cycling), system efficiency (electric transit systems connected to renewable energy grids), and a change in behaviour.

3.3.2. Transit-oriented development (TOD)

As far as mass transit is concerned, the past two decades have witnessed massive increases in investment in mass urban transit systems: bus rapid transits (BRTs), light rail systems and (still nascent) the potential for fleets of driverless cars. However, massive public sector investment in transit infrastructure, if not planned holistically, can sometimes result in unintended negative socio-economic consequences. For example, transit-related approaches that focus solely on mobility can result in increased land prices around the mass-transit nodes (primarily bus and rail stations). Anticipating this, private developers buy up land around these nodes and invest in property developments that generate the maximum profits (meaning they build as high as possible, sell to the highest Living Standards Measure [LSM] bracket as possible, and adhere to the minimum environmental and social requirements). In effect, this is urban rent seeking: private profiteering from public sector investments that push up land values. In such cases, the investment in transit infrastructure can unintentionally reinforce market dynamics and splintered urbanism. Instead of improving services for low-income citizens, it may create gentrified enclaves for the globally networked elites.

In contrast, an approach known as transit-oriented development (TOD) involves public sector strategies that are aimed primarily at urban regeneration and transformation, with investments in mass-transit systems being one of the means used to achieve these goals. TOD has been defined as "more compact development within easy walking distance of transit stations (typically half a mile) that contains a mix of uses such as housing, jobs, shops, restaurants and entertainment" (Reconnecting America, 2007). By promoting "compact, mixed-use, pedestrian-friendly development organized around a transit station", well-designed TOD not only increases usage of public mass-transit systems, but also "increases and serves as a hub for organizing community development and revitalizing long-distressed urban districts"(Cervero and Dai, 2014). An important element of the TOD approach can be the involvement of public-private partnerships that make it possible for the public sector to capture a portion of the improved land values (known as the "value-capture" approach) (Cervero and Murakami, 2009, Cervero and Kang, 2011). This can achieve two things: the substantial costs of the transit infrastructure are fully or partly recovered from resulting property developments (instead of just adding to public debt for the benefit of private profit); and it may also enable greater public control of the urban developments that emerge, thereby enabling improved environmental and social outcomes (Cervero and Dai, 2014). Some case studies of successful TODs are given in Part III - Section 7.4.4.

3.3.3. Efficient and renewable energy systems (ERES)

With regard to retooling the energy grids within which urban systems are embedded, a number of urban districts in Germany, Spain, Costa Rica and Kenya now secure all their energy from renewable energy sources. At the neighbourhood level there are now thousands of examples, including in cities of the Global South where informal settlements are accessing energy via off-grid solar home systems. Subregional and city-wide energy planning initiatives have emerged across all regions, often with substantial backing from funders. Over time — and as the costs of renewable energy technologies continue to fall (in absolute terms and relative to the rising costs of the alternatives) — these initiatives will result in the gradual build-up of increasingly autonomous renewable energy grids. District Energy Systems, which fit within this framework, are starting to emerge and demonstrate how extraordinary energy efficiencies can be realized (UN Environment, 2015).

3.4. Case studies

It is important to recall that, as noted in Part III - Section 3.1.1, different cities encounter a range of different opportunities and challenges, and have varying drivers for resource-efficient solutions, depending on their size, demographics, and also geographical locations. For example, some cities are located in areas where renewable energy sources are plentiful, and are thus well positioned to take advantage of these. In cities where water supply is stressed, drivers for water efficiency will evidently be stronger; cities with cold climates will have greater incentive to invest in keeping buildings warm, those in hot climates the reverse. Different cities also have different financial resources to invest in resource-efficient solutions, and different social conditions that could provide other drivers for resource-efficient strategies.

This section will discuss a number of examples of resource-efficient practices in cities, drawing evidence from a range of contrasting cities, with different conditions and drivers, across the world.

3.4.1. Improving the efficiency of energy and water use in cities

Cities are major consumers of energy services, but can also be particularly prone to wasting energy, especially in richer developed countries. Some cities are therefore undertaking investments in computer-controlled technologies that can reduce the time during which energy gets wasted. In Songdo, Republic of Korea, buildings have been fitted with computer-controlled lighting and temperature controls to minimize energy wastage (UN Environment, 2013a, p. 48, p. 64), while San Jose, California, has invested in LED street lighting connected via a smart network (UN Environment, 2013a, p. 48).

Structural investments in improving the efficiency performance of buildings are also common: Finnish municipalities, for example, have made such energy efficiency improvements to reduce CO_2 emissions (UN Environment, 2013a, p. 48). Meanwhile, building efficiencies in Melbourne, Australia, have been raised through mandatory energy efficiency performance codes, implementation of energy efficiency measures in public buildings and lighting, a house auditing programme, and a green office alliance, which works with commercial tenants (UN Environment, 2013a, pp. 72–73).


Photo: ©AFP

The Four Centres building at Red Deer College, Alberta, Canada shows the importance of design and simulation modelling in optimizing the energy performance of buildings. The buildings are designed to optimize natural light, with sensors automatically dimming electric lights when they are not required. Efficient ventilation design is combined with heat exchange to recapture heat from exhaust air, and the building fabric has high thermal resistance. The design process was guided by the Green Building Council's LEED certification process, and by computer modelling and simulation that helped test the energy and cost savings of alternative strategies. The result is a building that exceeds the minimum mandated efficiency standards by 61 percent (National Resources Canada, 2015).

As well as environmental impact and resource-conservation concerns, an important objective for improving building efficiencies is, in many cases, to improve the health and well-being of vulnerable, low-income citizens. The discussion in Part II - Section 5.2.5 on the Residential Energy Program in Boston and the Public Housing Fund in Ljubljana, Slovenia, shows ways in which programmes for local authority-led sustainable housing, with lower energy consumption and lower carbon emissions, can reach low-income households in cities in a developed country. There are similar multiple motivations — reducing carbon emissions, lowering the cost of energy services and improving the comfort of homes — behind actions taken in Totnes, UK, as part of the Transition Town initiative. However, this is an entirely community-led, bottom-up initiative. It has involved a number of neighbourhood groups of 6–8 households, 50 percent of them low income, being formed. These groups are working collectively to implement both technical and behavioural changes in their households (UN Environment, 2013a, p. 73).

In countries of the Global South, improvements in the building and construction sector are also crucial to addressing needs for housing, employment and public infrastructure, but in this case in a context of rapid urbanization and urban population growth. As an example, the Kuyasa project in Cape Town, South Africa, has seen energy-efficient light bulbs, insulated ceilings and solar water heaters installed in low-income housing buildings, reducing bills and improving the comfort of homes for the residents. Due to the CO_2 savings, the project also qualifies under the clean development mechanism (CDM[20]). The project has also provided local employment and skills development opportunities (UN Environment, 2013a, p. 48, 49, 75, 77). In the same city, a project with the Tygerberg Administration building in the Parow suburb (discussed in more detail in Part III - Chapter 1) has reduced energy use, expenditure and GHG emissions through introducing technological interventions and promoting behavioural change among the city staff who use the building.

At a much larger scale (again, see Part III - Chapter 1 for more detail), Green Mortgages Mexico has benefited more than 3 million people by facilitating the building of houses with energy-saving materials and using eco-efficient technologies to improve the service quality of water, electricity and gas. A comparable scale of innovation and change will be made increasingly necessary by the emergence of a large middle class in developing Asian countries, and emerging economies elsewhere, which is leading to greatly increased demand for houses. For example, as discussed in Part III - Chapter 1, 22 percent of all energy in India is used by the residential sector. Increased building and construction is, with current practices, expected to lead to an eightfold increase in the sector's overall energy use by 2050, compared with 2012. However, the Global Buildings Performance Network, also mentioned in Part III - Chapter 1, has shown how an aggressive policy- and market-driven strategy could reduce energy consumption projections by 57 percent relative to these projections.

A barrier to increasing the efficiency of consumer energy use is the lack of information available to customers, and their cost-sensitivity. This has been addressed within the EU by the Ecodesign and Energy Labelling Directives, which are projected to deliver an energy saving of 19 percent below the business-as-usual scenario by 2020 (Molenbroek et al., 2014). Mandatory standards are also possible. In Japan, the "Top Runner" scheme uses the performance of the highest performing energy-efficient appliances as a guide for setting the required average standard

20 A mechanism established within the Kyoto Protocol of the United Nations Framework Convention on Climate Change, to assist countries with emission-reduction commitments to transfer investment to emission-reduction projects in developing countries. The projects create certified emission reduction (CER) credits, which could be counted towards meeting Kyoto targets. See: http://unfccc.int/kyoto_protocol/mechanisms/clean_development_mechanism/items/2718.php.

in a future year. A review of the first 12 years of this programme confirmed its success in driving up energy efficiency performance and encouraging innovation: each targeted product group had met, and often exceeded, the required Top Runner standard. Efficiency improvements in different product groups ranged from 16 percent to 80 percent in the target year (Osamu, 2012).

In many cities, water supplies are under great pressure; hence water efficiency and water conservation become extremely important. Singapore has implemented water efficiency improvement and leakage programmes (UN Environment, 2013a, p. 48). Melbourne uses reclaimed water for irrigation, and extensive mulching to improve water retention. There is also a free showerhead exchange programme, whereby replacement showerheads reduce water usage by an average of 13,500 litres per person per year (UN Environment, 2013a, p. 73). Following a severe water crisis in 2003–2004 in Chennai, India, sustainable water management became a major priority. One community-led programme restored a historic temple tank to harvest rainwater as a means of replenishing the depleted aquifers (UN Environment, 2013a, p. 49, 75).

3.4.2. Use of renewable resources and ecosystem services/self-sufficiency

As discussed in Part III - Section 3.2, cities can be thought of as metabolisms, into which resources flow from outside, and from which waste is produced. As such, cities are highly dependent on and integrated with surrounding areas and their ecosystems. However, far from being entirely dependent on external sources for their resources, cities have the potential to produce resources and energy within their own boundaries, thereby reducing the metabolic flow of inputs from external sources. This section looks at some of the ways in which cities have increased their self-sufficiency in energy and food production.

Small-scale renewable energy generation is a viable option for many cities, with the appropriate

technology dependent on the location and climate. As part of the previously mentioned Transition Town initiative in Totnes, England, the community has formed a company with plans for four energy projects: a 4.5 MW wind farm, an aerobic digestion scheme, a biomass boiler, and four solar arrays of 30–50 kW peak capacity (UN Environment, 2013a, p. 73).

Solar PV and wind turbines generate electricity in Masdar, Abu Dhabi (UN Environment, 2013a, p. 49). In Portland, Oregon, US, 5 MW of solar PV has been installed on domestic and commercial buildings, supported by upfront financing (UN Environment, 2013a, p. 73). The city of Auroville in India is powered by 200 solar PV panels, and pumps its water using 140 solar water-pumping units and 30 windmills (UN Environment, 2013a, p. 66). Meanwhile, Vauban, in Germany, has a solar settlement of 50 houses, each of which is equipped with solar PV panels which generate more electricity than the residents consume (UN Environment, 2013a, p. 65).

Landfill sites occur within or close to some cities. Extracting and generating power from landfill gas is a well-established technology. For example, methane is used for energy generation at the Mariannhill landfill site in Durban, South Africa. The processed leachate is also used for irrigation and dust suppression (UN Environment, 2013a, p. 52, 68). In Växjö, Sweden, district heating is fuelled by waste woodchips from nearby logging activities (UN Environment, 2013a, p. 52).

Production of food within cities also reduces their resource dependence on external resources

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

and ecosystems. For instance, in Buenos Aires, Argentina, recurring economic crises and food shortages have inspired initiatives aimed at boosting local food production (UN Environment, 2013a, 2013, p. 74).

3.4.3. Reuse and recycling of waste and materials

As discussed in Part III - Section 3.2, and shown in Figure 65, urban metabolisms produce waste, which requires disposal. However, as shown in Figure 65 (b), the reuse and recycling of waste within the urban metabolism can improve the efficiency of the urban metabolism, by reducing both the required inputs of resources and energy, and the resulting waste outputs.

Cities produce large, widely distributed amounts of different types of waste. A major challenge to the successful reuse and recycling of urban waste is therefore collecting and sorting the waste that comes from large numbers of households and businesses. In many cities, the local government assumes most of the responsibility for coordinating the logistics and investing in the infrastructure to collect waste, which is then paid for through local taxes.

However, alternative approaches are possible. In Curitiba, Brazil, residents were incentivized to sort their organic and non-organic recyclable waste and bring it themselves to waste stations, by the offer of exchanging their waste for bus tickets, food and schoolbooks (WWF, 2012). In Vietnam's cities, syndicates of individual workers have organized themselves to collect household waste, liaising with local authorities to identify areas that require additional services, and gaining permission to collect in those areas from the local authority. Ho Chi Minh city has around 3,000 of these independent collectors, who are often far better able to navigate the narrow streets than large collection trucks would be. This approach

also creates more jobs than would be created in a truck- and machine-based collection and sorting system (UN Environment, 2013a, p. 77).

In some of India's large cities, rubbish picking, sorting and recycling is a major source of informal employment, however often with considerable health risks to those involved. As a result of this activity, plastic recycling rates in India are high — estimated at around 60 percent, compared with typically 10 percent in Europe and the US. However, most of this takes place in the informal sector, and worker safety is a major concern. In Delhi, for example, plastic recycling employs an estimated 20,000–25,000 workers. These can range from rag-pickers who collect waste from the streets and open landfill sites, to itinerant waste buyers who collect waste door-to-door, to owners of small plastic recycling units, of which approximately 7,000 exist in Delhi (Haarman, 2015). The sum of this activity results in high recycling rates and significant employment generation; however, evidently in dire working conditions for some of those involved. There may be an opportunity to capitalize on these networks that have arisen spontaneously, while introducing greater regulation to improve safety and working conditions.

In Kampala, Uganda, a community project was established to collect household organic waste for reuse as animal feed. This was developed via an intermediary organization, which brought together an international research project, the city council, local universities, civil society organizations and the local community itself (UN Environment, 2013a, p. 52, 68).

In Linköping, Sweden, biogas from digested organic waste is used to power the city's bus fleet (UN Environment, 2013a, p. 52, 76, 78). This activity displaces about 5.5 million litres of petrol and diesel each year, and reduces CO_2 emissions by more than 9,000 tonnes each year. It has also reduced waste sent for incineration by 3,422 tonnes per year. Furthermore, it generates fertilizer, which is used on local farms and generates income for the local economy.

In many cities, water availability and treatment is a serious concern, either due to climatic conditions or a lack of infrastructure. One simple technological solution, implemented in Lilongwe, Malawi, is the waterless toilet, which operates independently of piped water, and converts the collected human waste into agricultural fertilizer (UN Environment, 2013a, p. 52, 67).

Meanwhile, urban farmers in Accra, Ghana, unable to afford connection to the main water network, constructed their own alternative network to irrigate their farms with grey water (UN Environment, 2013a, p. 52, 67). In Beijing, China, legislation has now made it compulsory for hotels and public buildings over a certain size to implement grey-water systems in order to reuse wastewater in uses such as toilet flushing and irrigation (UN Environment, 2013a)(p. 67).

3.4.4. Transport

Mobility is a critical need in large cities, as it affects citizens' access to jobs, services and amenities. Affordable public transport has environmental and resource benefits, as it typically enables more resource-efficient transportation than private modes, as long as there is sufficiently high use of public transport. It can also have significant social impacts by enabling the interconnectedness of a city, and working against the isolation of communities on the basis of their income.

One of the key challenges for low-income urban dwellers is paying the travel costs to access employment many miles from their homes. In Medellín, Colombia, a cable car system now connects poorer communities living on the mountain slopes to the city centre, thus generating social benefits (UN Environment, 2013a, p. 48, 67). Part III - Chapter 1 describes how in 1990 the Municipality of Lima in Peru took an innovative approach to make resource-efficient transport more affordable for low-income households, by setting set up a micro-credit programme to help low-income citizens purchase bicycles.

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

Photo: ©CC by Natasia Causse

Bus rapid transit (BRT) systems have been implemented in about 160 cities across the world, notably in Latin America where leading countries include Brazil, Colombia and Mexico (Cervero and Dai, 2014). China has been a fast adopter of BRT systems in recent years, while challenges with traffic and congestion have also prompted mass-transit investments in emerging megacities such as Lagos, Nigeria, and Bangkok, Thailand (UN Environment, 2013a). As previously described in Part III - Section 3.3.2, a transit-oriented development approach can be key to ensuring that the social as well as environmental benefits of transport infrastructure investments are maximized and equitably distributed. A balance of roles between the public and private sectors is often an important part of this.

Cervero and Dai (2014) cite Ottawa (Canada) and Curitiba (Brazil) as leading global examples of TOD based around BRT systems. In both cities, investments in transport technologies and infrastructure were of course a major part of the strategy. For example, Curitiba's system makes use of cleaner vehicles and fuels, and infrastructure arrangements such as "passing lanes at stations to increase capacity and improve commercial speeds" (Lindau et al., 2010). In both cases, the local governments also had a significant role in setting out the long-term vision for the new urban developments, and using the BRT system as a means to "channel growth along well-defined linear corridors" (Cervero and Dai, 2014). Local governments were proactive in leveraging the benefits of TOD, with additional supporting policies including "zoning reforms, pro-development tax policies, assistance with land assemblage, and supportive infrastructure investments". In Curitiba, local government "mandated that all medium- and large-scale urban development be sited along a BRT corridor". Through such means, public policy can be used to guide private sector investments in a way that best leverages the benefits of transit-oriented development (Cervero and Dai, 2014).

A further social challenge associated with public transport investment, also mentioned in Part III - Section 3.3.2 above, is the impact of price increases associated with the increased desirability of neighbourhoods served with good transport links. This can result in private sector property investors taking the benefit of public sector investments, due to the increased property and rental values that are stimulated as a result. For example, evidence suggests that

BRT improvements in Seoul, Korea may have contributed to land price premiums of 10 percent for residential properties within 300m of a BRT stop, and of 25 percent for commercial properties within 150m of a stop (Cervero and Kang, 2011). Similarly, evidence from Hong Kong suggests that housing price premiums in the range of 5–30 percent can be observed for properties with good access to the rail transit network (Cervero and Murakami, 2009).

Returning some of this increased value to the public purse then becomes a legitimate public policy objective. As such, there is a strong case that investments in public transit should be accompanied by a clear plan as to how the wider economic benefits of the investments may be captured and equitably shared. In the Hong Kong case, a value-capture approach was used, which enabled increased income from property values to be returned as investment into transport infrastructure. Under this "Rail + Property" development programme, "more than half of all income to the railway operators comes from property development" (Cervero and Murakami, 2009). However, even if some of the value of rising property prices can be recaptured for reinvestment in transport infrastructure, the rising property values themselves could still have other inequitable social effects, such as the displacement of existing lower-income residents who can no longer afford to live there.

Photo: ©CC by Secretaria de Movilidad de Medellin

An interesting qualification on the issue of the affordability of TODs for residents is provided by Renne et al. (2016). In reviewing over 4,000 transit station areas across the US, they find evidence that while those classified as TODs generally have higher housing costs, they may be less expensive places to live overall, due to the lower cost of transportation. However, outcomes could vary in different locations, depending on the extent of the housing cost premium, and the baseline transport activity of a given household prior to the TOD investment.

Overall, given the strong evidence for property premiums associated with TOD areas, there is reason to conclude that a socially responsible TOD strategy should consider the potential impacts on lower-income households of increased housing costs. For example, as noted by Cervero and Kang (2011), "one possible use of revenues recaptured from benefitting property owners is to underwrite the costs of providing affordable housing and shops to displaced residents and merchants".

3.4.5. Urban design and integrated visions and concepts

The story of many large cities is one of unplanned expansion; an aggregated result of the various activities of the citizens that live, work and build there over successive generations. In such a situation, the challenge for an urban planner wishing to make a resource-efficient intervention, is to do so in a way that can negotiate through the deeply embedded physical infrastructures and cultural practices that characterize the city. However, in other cases, there are opportunities for a more fundamental approach that embeds the planner's desired principles into the design of the urban environment itself. Clearly, this kind of opportunity is often found when whole cities or districts are being planned and constructed from scratch.

Cervero and Sullivan (2011) discuss examples of what they call "Green TODs". In such examples, the TOD principle (as discussed

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

in Part III - Section 3.4.4) is joined with other aspects of green urbanism that aim to reduce energy and emissions from stationary sources, water pollution and waste, and to increase green spaces. There are a number of beneficial synergies potentially available from considering multiple resource flows and services in an integrated sustainable urban design. High population densities are important to optimize usage of public transport systems, and they also typically result in lower energy use per person for heating and cooling. Higher densities also improve the viability of shared infrastructures that can help optimize energy and resource use, such as district heating networks, and local energy recovery from wastewater and municipal waste. In terms of design features, mixed land use — the integration of residential buildings with shops, workplaces and other amenities — helps reduce the need for travelling long distances. It can also create opportunities to match the energy and waste profiles of different types of buildings: for example, waste heat from commercial premises being reused as residential heat through district heating networks. The reduced need for private vehicle transport that arises from a TOD approach has the additional benefit of reducing the land area taken by parking spaces, which can increase the number of green spaces, reduce heat-island effects and improve groundwater recharging. Train and bus depots and stops also provide roof spaces that can be well utilized for energy production, for example from solar photovoltaic (PV) panels (Cervero and Sullivan, 2011).

Vauban, Germany, is an eco-city development near the city of Freiburg, situated on the site of a former army barracks. Planned and designed as a new integrated development, it provided an opportunity to embed sustainability into the design of the project itself. All of the houses meet, and many exceed, the energy efficiency standard set by the city of Freiburg of 65 kWh/ m^2/year, and the community includes one of Germany's largest Passivhaus (Passive House) developments, as well as a solar-village. Energy is also provided by a combined heat and power plant fuelled by waste woodchips. The area has been designed to actively discourage car use, with significant speed restrictions, and most houses having no driveway or garage. A communal car parking facility is available on the edge of the town, but it is relatively expensive to hire a space. By contrast, the layout of the district actively encourages walking and cycling, with all residents living within two minutes of covered bike parking and five minutes of a tram stop. The tramway spine threads through the town and also connects it to the centre of Freiburg. There is also an extensive network of pedestrian and cycle paths, including access to the city centre via separated cycle paths. The design of Vauban appears to have resulted in low car use, with only 22 percent of residents owning a car, and 57 percent of residents reporting having sold a car upon moving to the district. In addition, the urban design allows for green spaces, permeable surfaces, and rainwater collection (Cervero and Sullivan, 2011).

Hammarby Sjöstad is a brownfield redevelopment in Stockholm, Sweden, which also has TOD and urban sustainability embedded into its design. A tramway runs through the community, with high-density six- to eight-storey buildings clustered along it. A new ferry service is provided, as well as cycle paths along the main boulevards, and all buildings provide cycle parking. The presence of car-sharing companies reduces the need for car ownership, with an average of 0.25 parking spaces per dwelling unit. Heating and cooling needs are largely met by district energy systems, and buildings are well-insulated. The development has aimed for a "closed loop" energy and resource infrastructure, with recycling and energy recovery. This is facilitated by a system of vacuum tubes into which residents deposit waste, which is then carried through the system to collection location points. This avoids the need for trucks to collect waste from each doorstep, which in turn reduces traffic. Storm water, rainwater and snow melt is collected and purified, and wastewater sludge is used to create biogas which provides fuel for the district heating network. An environmental impact profile carried out between 1997 and 2002 found that the development had significantly

reduced impact compared with a reference level of a conventional contemporary Stockholm development, including a 32–39 percent reduction in overall emissions and pollution, and a 28–42 percent reduction in non-renewable energy use (Cervero and Sullivan, 2011).

Other examples of very low-energy housing described in Part III - Chapter 1 are the Towards Zero Carbon Development (T-Zed) project in Bangalore, India, and the Beddington Zero Energy Development (BedZED) community in the UK.

3.5. Overcoming barriers

Accelerating the increase of urban productivity through restructuring neighbourhoods, TOD investments and inclusive and smart renewable energy grids will depend on the modes of urban governance. These modes will emerge as new interactions between urban actors generate leadership coalitions to realize the potential of accelerated urban transitions. This will take vastly different forms across different contexts: in cities of the Global North with well-developed urban infrastructures, city-level leadership will be faced with the challenge of "lock-in" and "sunk costs" if they are seriously committed to retrofitting. On the other hand, in cities of the Global South that have not yet sunk in concrete 19th/20th Century technologies, the challenge will be to secure and build the necessary institutional capacity for implementation. There is also the need to overcome the modernist aspiration to "be like the West", which has been the cause of such disasters in China's vast new urban agglomerations.
The International Resource Panel's Decoupling Report (UN Environment, 2013a) argued that the key factor that determines whether or not an urban transition occurs in a given city or town is whether there are any intermediaries who can access new knowledge about alternatives and bring to bear additional capacity for managing the change process. These intermediaries can be university researchers, NGOs, citizen coalitions, local government policy units or business groupings: there is a unique configuration in each specific locality.

3.6. Conclusions

There is a huge range of opportunities for resource efficiency at the urban scale. These vary from high-tech to simple solutions; and solutions that have been developed by processes and actors that include bottom-up community-led approaches as well as top-down local or national government initiatives. Particular conditions vary widely between different cities, including in the natural resources available, the challenges presented by the regional climate and topography, and the degree to which large infrastructure is already embedded and locked in.

Successful interaction between a variety of actors and the potentially important role of intermediaries have been behind many of the case studies of resource-efficient urbanism. Indeed, urban environments present so many opportunities partly because they are "hotspots" of interaction of many different human activities. Urban policymakers need to be open to diverse solutions, and not necessarily look for one-size-fits-all solutions. Lock-in created by urban infrastructures can be a major challenge, and similarly planners for the future should beware of creating their own undesirable lock-in effects.

There is often a role for the kind of holistic planning and coordination that can be provided by a central vision, either from the local or regional government, or from a private sector designer. Especially in spatially networked infrastructures, these kinds of holistic approaches can yield significant resource efficiency benefits, for example through integrated transport and mixed-use planning. However, it is also worth recalling that impressive examples of resource-efficient innovations have also been seen to occur in bottom-up, community-led or spontaneously evolving processes. Therefore, top-down planning approaches should also be mindful of the potential available in existing social capital and community networks. The challenge is to combine the integratory and holistic benefits of top-down intervention with the potential for community-led creativity and bottom-up innovation.

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

4. RESOURCE-EFFICIENT FOOD SYSTEMS

4.1. Introduction

4.1.1. Dependence of food systems on natural resources

Food systems are critically dependent on natural resources, such as land, soil, water, biodiversity (including marine resources), minerals and fossil fuels. Currently these resources are often not managed sustainably or efficiently, leading to degradation or depletion of resources and thus to risk for future food security (see Box 10). Food production also has a major impact on the environment, for example due to greenhouse gas emissions, nutrient losses and depletion of fish stocks. Natural resources are also used along the rest of the food chain (e.g. in producing, processing and packaging, storing and transporting, and retailing and cooking food), causing significant environmental impacts, which are in many cases increasing. The key question is how governments, together with private actors, can stimulate more resource-efficient food systems, while simultaneously contributing to better outcomes in terms of food security, nutritional quality and human health.

4.1.2. Food systems: a powerful lens to look at food consumption and production

Following the High Level Panel of Experts on Food Security and Nutrition of the United Nations Committee on World Food Security, a food system is here defined as "all the elements (environment, people, inputs, processes, infrastructures, institutions, etc.) and activities that relate to the production, processing, distribution, preparation and consumption of food, and the outputs of these activities, including socio-economic and environmental outcomes" (HLPE, 2014). In contrast to the food chain concept, which perceives different actors and their activities more neutrally, the food system concept acknowledges that the actors not only influence each other but are also influenced by other actors, such as NGOs and civil society groups. Food systems

Box 10: Some key facts and figures

1. In nearly all countries land degradation occurs, implying an unsustainable use of land. Globally, an estimated 33 percent of soils is moderately to highly degraded due to erosion, nutrient depletion, acidification, salinization, compaction and chemical pollution (FAO, 2015a, FAO, 2015b). However, accurate data are lacking. Climate change may increase land degradation and challenges to food production.

2. At least 20 percent of the world's aquifers are overexploited, including in important production areas such as the Upper Ganges (India) and California (US) (Gleeson et al., 2012).

3. The nitrogen and phosphorus-use efficiency (from farm to field) in the global food chain is around 15–20 percent, implying large nutrient losses to the environment (Sutton et al., 2013). Some regions have lower efficiency and higher losses (North America, East Asia), while in sub-Saharan Africa soil nutrient depletion (where nutrient extraction is higher than input) is common.

4. Globally, food systems account for around 24 percent (21–28 percent) of global greenhouse gas emissions (FAO, 2014a, Vermeulen et al., 2012). In developed regions, the share of agriculture in total GHG emissions is typically around 10 percent (EEA, 2015, EPA, 2015), with considerable additional emissions related to the use of fossil fuels in the food chain (for processing, transport, cooling and preparation of food; as well as for the production of fertilizers (>1 percent of global energy use)) (IFA, 2009).

5. Globally in 2013, 58 percent of fish stocks were fully fished, while 31 percent of fish stocks were estimated to be "fished at a biologically unsustainable level and therefore overfished" (FAO, 2016b).

6. Food systems activities are also a major source of both terrestrial and marine biodiversity loss (Chaplin Kramer et al., 2015, Coll et al., 2016, PBL, 2014a).

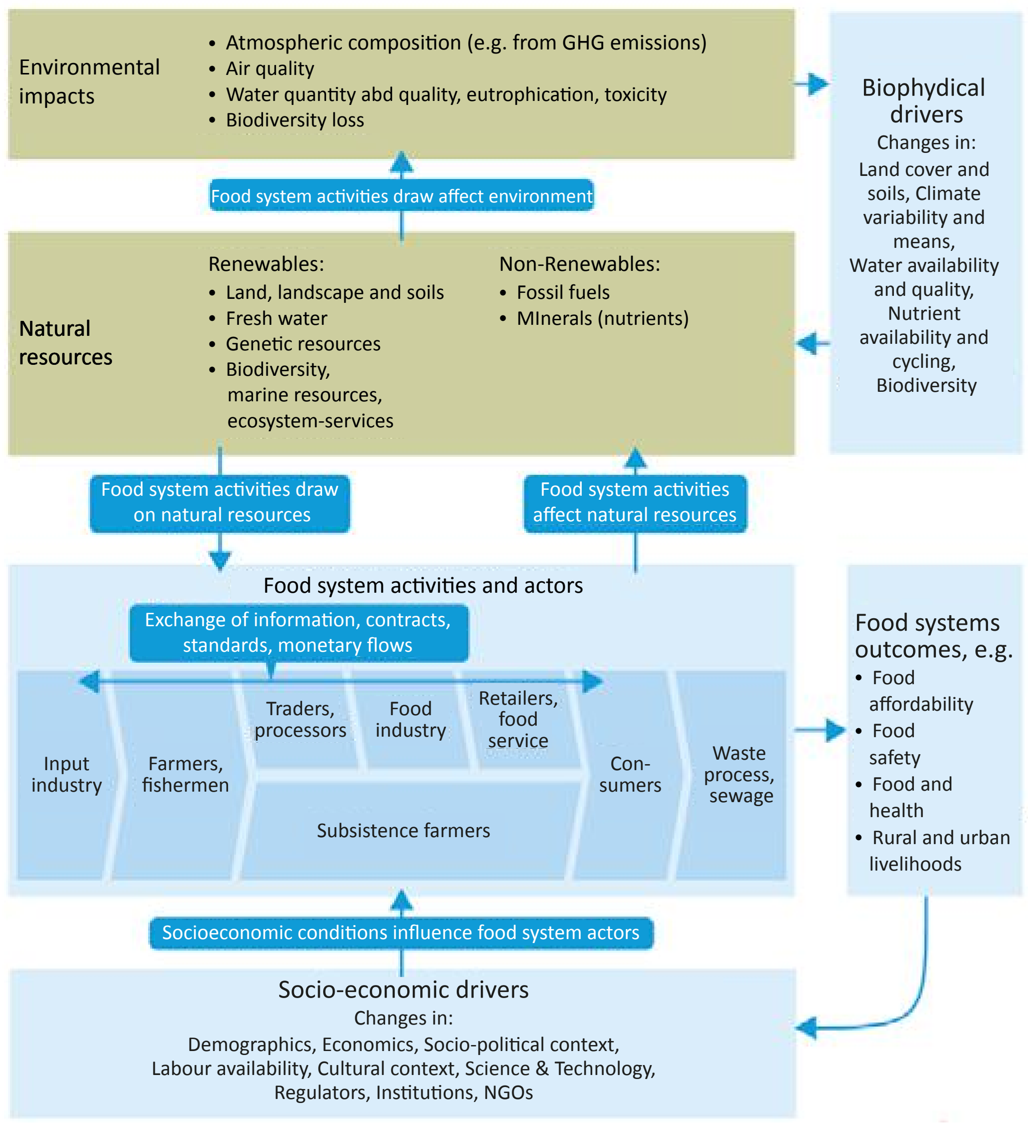
7. Nutrient losses to ground and surface waters lead to massive algae blooms and "dead zones" ("hypoxic") in coastal areas around the globe (Rabotyagov et al., 2014).

significantly differ around the world, ranging from the more "traditional" (which are still often based on subsistence farmers operating locally) to "modern" (which are multi-actor, complex and international in character) (Reardon and Timmer, 2012).

4.1.3. Natural resources and environmental impacts

The natural resources needed for food system activities can be divided into renewable and non-renewable resources (UN Environment, 2011a). **Renewable resources** stem from renewable natural stocks that, after exploitation, can return to their previous stock levels by natural processes of growth or replenishment. This is possible provided they have not passed a critical threshold or "tipping point" from which regeneration is very slow (e.g. soil degradation) or impossible (e.g. species extinction). Crucial renewable resources for food systems are soil, water (for both primary production and processing), biodiversity (including genetic and

Figure 67: Conceptual framework of food systems, natural resources and environmental impacts



marine resources) and, for many, biomass fuels for cooking.

According to the OECD, "**Non-renewable** natural resources are exhaustible natural resources whose natural stocks cannot be regenerated after exploitation or that can only be regenerated or replenished by natural cycles that are relatively slow at human scale" (2002). Crucial non-renewable resources used in food systems include minerals (plant nutrients, such as phosphorus and potassium, and other mined resources such as lime), groundwater and fossil fuels.

All food system activities have an **impact on the environment** to some degree and most of these impacts are intrinsically related to the use of natural resources in food systems. For example, the use of fossil fuels leads to CO_2 emissions, while the use of minerals to promote crop production often leads to nutrient losses to groundwater and surface water. The positive side of this is that a more efficient or

sustainable use of natural resources usually leads to a reduction in environmental impacts, creating many synergies. Concrete examples of these synergies are better targeted fertilization, leading to lower resource use (minerals), as well as to lower nutrient losses, and higher fuel efficiency along the food chain, leading to lower CO_2 emissions, reduced food packaging (without jeopardizing food safety or increasing food waste), and better management of fisheries to conserve biodiversity. Both the degradation of natural resources as environment impacts can lead to a reduced provision of crucial ecosystem services.

4.1.4. Importance of both "sustainable" and "efficient" use

In order to guarantee a continued supply of food for current and future generations, it is important that renewable natural resources are managed both **efficiently** and **sustainably**. Here we use the word sustainable in a strict sense, simply meaning that the use of the resource can continue in perpetuity, because the resource is not degraded or depleted at a faster rate than it can be renewed.

In line with the nomenclature developed in Part I - Chapter 2, the efficiency of resource use may be considered in terms of (i) *productivity* (output per unit of resource input) or its reciprocal value *resource intensity* (resource input per unit of output); and (ii) *technical efficiency*, considering such issues as losses or degree of recycling. The latter aspect is notably important for minerals, where the nutrient-use efficiency can be calculated over the whole food value chain. A food system can be considered **more resource-efficient** when more food is produced and finally consumed with the same amount of resources, or when the same amount of food is produced and finally consumed with fewer resources (UN Environment, 2011b).

It is important to note that in the case of crop production in particular, resource efficiency has to be evaluated for the **combined, large number of natural resources** on which crop production is based. For example, applying mineral (nitrogen) fertilizers will, in many cases, increase crop yield, and thus land productivity. However, at the same time the (marginal) nitrogen-use efficiency decreases. From the point of view of nitrogen-use efficiency, less fertilizer is better, while from the point of view of land and labour productivity more fertilizer is usually better. This calls for a balanced input and use of all resources, in order to optimize the overall resource efficiency. The efficiency of one resource also often depends on other resources.

4.1.5. Unsatisfactory food security and health outcomes

Current food systems deliver ample and safe food to many people in the world on a day-to-day basis, which can be regarded as a great achievement. However, for various reasons, in many cases food systems fail to deliver the right amount or quality of food: globally 800 million people are still hungry (FAO, 2015c). Paradoxically, over 2.5 billion people are overweight or obese (Ng et al., 2014) and often suffer from food-related diseases due to unhealthy eating habits. In total, globally over 2 billion suffer from micronutrient deficiency (FAO, 2015c, ICN2, 2014), a number which also partially includes the above-mentioned hungry, overweight and obese populations. In the G7 countries, the rate of people who are obese or overweight has increased sharply over the last decades (OECD, 2014a). This rate is now around 40 percent in France, Italy and Germany, and around 60 percent in the US, Canada and the UK. Only in Japan is the rate considerably lower. In particular, meat consumption in most industrialized nations is much higher than is deemed to be healthy. In the EU currently, protein intake is 70 percent higher, and saturated fats 42 percent higher, than the World Health Organization (WHO) recommends (2007), while red meat consumption is more than twice the maximum recommended by the World Cancer Research Fund (WCRF and AICR, 2007, Westhoek et al., 2015).

4.2. Potential

There is great potential to make food systems *use natural resources more efficiently*, as well as to improve the *sustainability* of the use of renewable natural resources such as land and marine resources. There are three main routes — the first targeting food production, and the latter two food consumption:

1) Enhancing the sustainable and efficient use of natural resources in **food production**, both at the level of farms and fishery operations, **as well as in food processing, transporting and retailing**. In most cases, this will in parallel result in a lower environmental impact of the whole food system.

2) **Reducing food waste**. For example, in the United States, 31 percent of the available food supply at the retail and consumer levels in 2010 went uneaten (Buzby et al., 2014).

3) **Changing eating patterns towards healthier and less resource-intensive diets**, involving moderate consumption of meat and dairy products in particular (Westhoek et al., 2011, Stehfest et al., 2009, Tilman and Clark, 2014, Westhoek et al., 2014). In affluent sections of society, consumers' intake of saturated fats and red meat is often too high. Limiting the intake of meat and dairy products has a positive impact on the resource efficiency of all resources. In the EU, for example, halving the consumption of meat and dairy products would reduce nitrogen emissions by 40 percent, greenhouse gas emissions by 25–40 percent, and per capita cropland for food production by 23 percent (Westhoek et al., 2014).

There are numerous ways to *use natural resources more efficiently* in food production. Some examples ARE:

- Increasing crop yields in a sustainable way, thus making more efficient use of land. There is considerable potential for this, especially in developing regions (notably sub-Saharan Africa), but also in developed regions (FAO, 2011b, Mueller et al., 2012, Neumann et al., 2010, Phalan et al., 2014).
- Increasing water-use efficiency, for example by reducing losses in irrigation systems by applying more efficient application techniques and precision irrigation (Comprehensive Assessment of Water Management in Agriculture, 2007, De Fraiture et al., 2014, HLPE, 2015).
- Reducing nutrient losses in crop production (mainly relevant for nitrogen) as well as in livestock production, especially by promoting the recycling of nutrients in the feed–manure–crop production loop. In parallel, this will lead to lower nutrient losses to the environment (Bouwman et al., 2013, Ma et al., 2010, Sutton et al., 2013, Sutton et al., 2011). Another important route is to improve the recycling of nutrients in the food system, for example by composting waste from households, restaurants and food processing facilities. Sutton et al. (2013) suggest an aspirational goal for a 20 percent relative improvement in full-chain nitrogen-use efficiency by 2020. This would lead to an annual global saving of around 20 million tonnes of nitrogen, which would reduce ammonia emissions as well as nitrogen run-off to freshwater and coastal environments, thereby limiting eutrophication and the associated biodiversity loss.
- Reducing the use of fossil fuels both on- and off-farm, for example by less, or more efficient, transport or by more efficient cooling (FAO, 2011a).
- Reducing the amount of energy and water used in food processing, for instance "dry extraction" of plant-sourced protein (Schutyser et al., 2015).
- Better matching land use with land potential (UN Environment, 2016e). Different crops and crop production systems are more productive and sustainable in different soil-climate combinations. Reorganizing land use to optimize sustainable productivity is one of the simplest options where appropriate policy levers exist or can be created.

- More integrated systems, at farm and landscape levels, as a way to improve resource efficiency.

Also in the case of a more **sustainable use of natural resources in food production and other food system activities**, many actions have strengthened the potential of a certain resource to support future food production (in the form of agriculture or fisheries). The type or scale of interventions needed, as well as their consequences, varies widely depending on the resource. Important actions include:

- Giving more attention to land and soil quality, for example by managing soil to increase soil carbon content and improve soil biodiversity; and by maintaining certain landscape elements to prevent soil and water erosion (USDA, 2011). Which measures are the most effective is very site-specific.
- Balance water extraction from aquifers with replenishment, to prevent lowering of groundwater tables (FAO, 2011c).
- Limit fish yields to an ecologically sustainable level, to prevent overexploitation of fish stocks. Capture fisheries' production appears to have reached a ceiling; additional fish production will have to come from aquaculture (OECD and FAO, 2014). Also in aquaculture, sustainable resource management is very important, ranging from the source of fish feed to the avoidance of water pollution due to fish excrement.

In many cases, much of the technology needed to make considerable progress is already available. In the case of food waste and changing eating patterns, human behaviour is a key entry point (Quested et al., 2013, Yoshikawa et al., 2016). In some cases, new technologies might be helpful; ranging from better storage techniques to software supporting behavioural change (Nunes et al., 2016, Dou et al., 2016). The necessary technologies are also often available to make big improvements at the production side, but there are various reasons why these technologies are not implemented — ranging from cheap inputs, to unpriced externalities and to the economic functioning of food systems (Van Doorn and Verhoef, 2015, Reczkova et al., 2013). Meanwhile, major food retailers are working hard to reduce overall energy consumption (e.g.

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

through more efficient cold shelving) and primary packaging (The Co-op, 2015).

Combining the approaches mentioned above (more efficient production, reducing food waste and changing consumption patterns) could substantially reduce resource use and environmental impacts. As improving resource efficiency in food systems is still quite an innovative approach, there are still relatively limited data on what can be achieved at a national or global scale. However, for some impacts or resources, such as greenhouse gas emissions and land use, it has been suggested that a reduction of 10–40 percent seems to be achievable, depending of course on the magnitude of changes and interventions (Westhoek et al., 2011, PBL, 2012, PBL, 2014b, Westhoek et al., 2014).

When striving for a more efficient production, often only one resource is addressed: targeted fertilization for example, which can improve nutrient-use efficiency, but will not (or will only marginally) improve water-use efficiency. Many efforts and initiatives focus on the production side, especially on improving farm management (SAI, 2012, USDA, 2011, JRC, 2015). However, options at the consumption side can also do much to increase the overall efficiency of the food chain (Westhoek et al., 2011, Stehfest et al., 2009, Tilman and Clark, 2014, Westhoek et al., 2014). The two routes aiming at reducing food demand (lower food waste and different eating patterns) will lead to lower per capita food production, but this has to be seen in the context of an increasing population and a global increasing demand for food. At the global level, it is thus rather a case of producing a "smaller increase" than absolutely less.

4.3. Evidence

The evidence for potentially more efficient and sustainable use of natural resources in presented in respect of the three main routes mentioned above. With regards to the first route (the *efficient* use of natural resources in **food production**), many actions have already been taken in recent years (and decades). In many cases, the efficient use of resources is consistent with the private interests of farmers and other actors in the food chain. Over the last 15 years, crop yields have increased by 10–40 percent in OECD countries (depending on the crop) (OECD and FAO, 2014). Furthermore, fhave been increased (Hoffmann, 2010). These improvements especially occur when certain resources or inputs are expensive, such as land (in many regions), feed and fuel. Other relatively cheap resources, such as nutrients, thus lack an incentive for efficient use. In the case of nitrogen in the EU, a targeted policy (the Nitrates Directive, implemented through national policies) has led to a significant reduction of nitrogen losses (and thus higher nitrogen efficiency) in the EU. In countries such as Belgium, Denmark and the Netherlands, the nitrogen surplus has decreased by 30 percent or more (van Grinsven et al., 2012). In developing countries, the lack of access to one or more resources or inputs (such as improved seed, pest control, fertilizers or water) is often the cause of low land productivity.

Information on the degree to which natural resources are used in a *sustainable* way is often lacking, with some exceptions. As stated above, good aggregated data on the status of land and soil quality and biodiversity are lacking. However, gradually more is becoming known about the state of fish stocks. The Netherlands provides as example for fisheries, as its share of MSC-certified fish has increased significantly, mainly because supermarkets (pressured by NGOs) made MSC the "default" choice for many fish species (see Box 11).

Reducing food waste is an obvious way of reducing pressure on natural resources. As already noted, large amounts of food are wasted at various points in the food chain, due to a large number of reasons. In affluent countries especially, the amount of food wasted by households and the food services (catering,

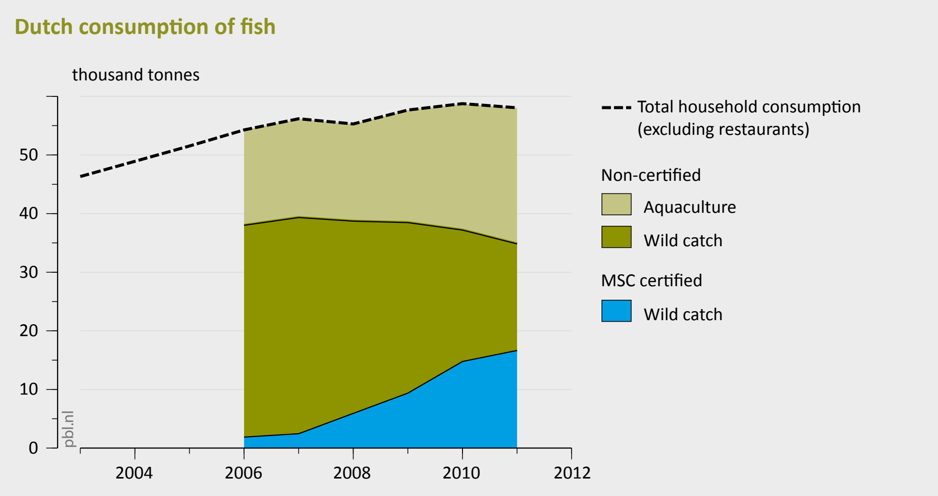
Box 11: MSC and the Netherlands

The Marine Stewardship Council (MSC) was founded in 1997 as a joint project between the World Wildlife Fund and Unilever. During a two-year process they developed a set of criteria for sustainable and well-managed fisheries, which was used from March 2002 onwards as a label on products (PBL, 2014b). In 2008, Dutch supermarkets set the goal to sell only sustainable fish by 2011, mainly focusing on MSC and ASC (Aquaculture Stewardship Council) certified products. At the end of 2011, around 85 percent of the supply of fish in supermarkets (fresh fish and frozen fish from private labels (own brands)) was MSC-certified (or comparable). No specific targets are set for other brands.

The amount of MSC-certified products consumed has increased considerably: from 6 percent of consumption in 2007/2008 to almost 40 percent of consumption in 2011/2012 (PBL, 2014b). This is lower than the share in supermarkets as a result of a lower percentage of MSC-certified products in specialized shops and fresh produce markets. MSC did lead to economic benefits for some fisheries as it provided market access and price advantages (PBL, 2014b). The higher price enabled fishermen to adopt new, less harmful fishing techniques. A positive side effect is that the new methods require far less fuel. As the ASC label was introduced only in 2013, consumption data are still lacking.

The Dutch government played a facilitating role, partly by subsidizing the cost of the development of certification schemes, and partly by fiscal measures that supported investments in new fishing gear.

Figure 68: Development of the consumption of MSC-certified and non-certified fish in the Netherlands



Source: MSC International, 2012.

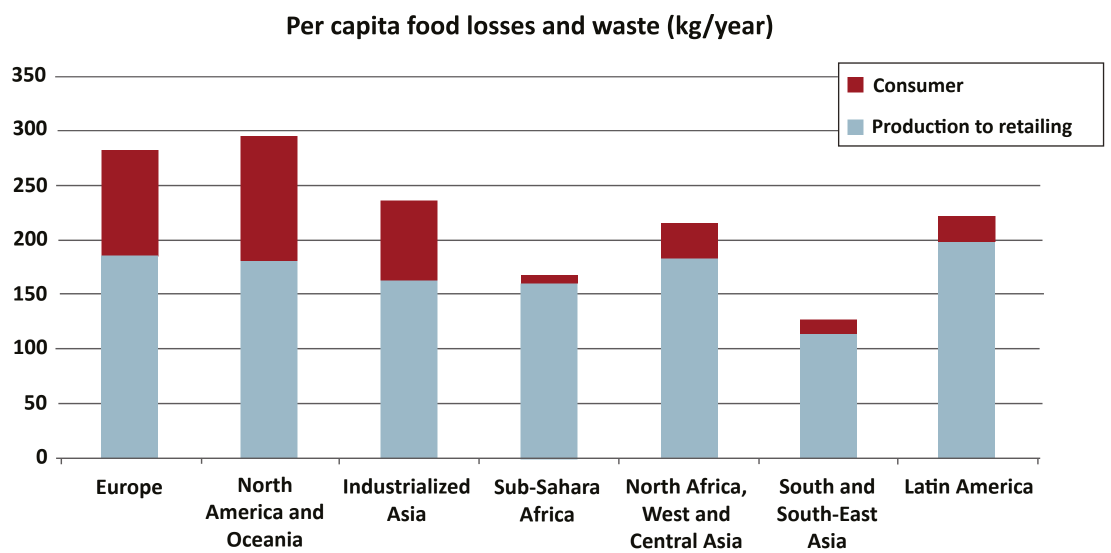
Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

restaurants etc.) is high. In the UK, the government and industry have initiated a specific programme to reduce such waste (see Box 12).

Reducing food waste is also a major resource efficiency opportunity. Figure 69 shows the quantities of food losses and waste per capita, at consumption and pre-consumption stages, in different world regions (although it is increasingly recognized that it is not restricted to countries per se, but the affluent middle and upper classes globally, even in the poorest regions). The figure shows that there are high levels of consumer waste (consumers throwing away unwanted food) in industrialized countries, although not insignificant levels in many developing regions. Supply-chain waste is also significant in industrialized countries, due to economies of scale and the "supermarketization" process, whereby high levels of waste are a by-product of a system geared towards ensuring shelves are continuously stocked with products that meet high uniform cosmetic standards, as well as basic food quality standards.

The Courtauld Commitment, convened by WRAP in the UK, is an agreement among retailers and suppliers designed to reduce waste. During its second phase (2010–2012), it worked with retailers to reduce packaging and increase the shelf-life and fridge-life of foods. It reports that during the same period, food packaging was reduced by 10 percent, wasted household food and drink by 3.7 percent, and supply-chain wastage by 7.4 percent (WRAP, 2016a).

Figure 69: Per capita food losses and waste, at consumption and pre-consumption stages, in different regions



Source: Gustavsson et al., 2011.

Part III: Increasing resource efficiency: best practices and case studies

Box 12: Courtauld Commitments convened by WRAP UK

WRAP, registered as a charity and a company limited by guarantee, is funded by the UK Government to support its waste prevention and resource efficiency policies. WRAP works in the space between governments, businesses, communities and innovators and brings actors together around initiatives for sustainable resource use through various mechanisms. One of these mechanisms is the Courtauld Commitment coordinated by WRAP.

The Courtauld Commitment is a voluntary agreement that brings together the industry and retail sectors, aimed at resource efficiency and waste reduction in the UK retail sector. The agreement commenced in 2005, with leading retailers, brand owners, manufacturers and suppliers signing up. Since its inception, participants have been adopting more and more ambitious targets and expanded their scope into new topics. Initially, participants were aiming to halt the growth in packaging waste, while at later stages more efforts and concrete targets were set on reducing carbon emissions, reducing food losses and waste and making financial savings through efficiency. For the post-2015 phase, the participants are negotiating goals and broadening the focus onto optimizing value chains and resource efficiency, supporting consumption behaviour change, sustainable sourcing and design, and maximizing the value of unused resources. These commitments have so far had the following concrete results:

- Avoidable household food waste was cut by 21 percent between 2007 and 2012, saving UK consumers almost GBP£13 billion over the five years;
- Between 2010 and 2012, household food waste reduced by 3.7 percent, while supply-chain and packaging waste dropped by over 7 percent;
- Between 2005 and 2010, 3.3 million tonnes of CO2 emissions were prevented, while between 2010 and 2012 the carbon impact and tonnage of waste was reduced by over 10 percent.

WRAP has also established a Product Sustainability Forum, which provides a platform for organizations to work together to measure, reduce and communicate on the environmental performance of grocery and home improvement products. Another programme run by WRAP is the "Love Food, Hate Waste" initiative, which is a consumer campaign aimed at awareness-raising and behaviour change among citizens. Despite this significant drive to reduce food waste, UK households are still throwing away 7 million tonnes of household food and drink annually, the majority of which could have been eaten.

Source: http://www.lovefoodhatewaste.com/content/about-food-waste-1

Supply-chain waste also occurs in developing countries for a range of reasons. For example, Feedback (2015) reports on factors driving food wastage in the Kenyan horticultural export sector. These include the need to discard edible food due to exacting cosmetic specifications, market volatility causing orders to be cancelled after crops have been grown, and the lack of domestic markets for export products. One example is given of the effectiveness of simply relaxing cosmetic standards. Supermarket retailers of French beans typically require the beans to be of a specific length to fit uniformly into packaging. This means that farmers must grow long bean varieties and

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

then "top and tail" them to the required length. Feedback (2015, p. 15) reports that this results in an average wastage of 30–40 percent of the usable mass of beans. However, one major customer was persuaded to change its buying policy and opt for just topped beans, enabling Kenyan exporters to reduce waste by a third. Further gains would be available if "topping" of French beans was also eliminated; and more still if cosmetic standards on other products were also relaxed.

Supply-chain waste in developing countries can also be caused by poor storage and processing conditions. In such cases, significant resource efficiency gains may be achieved through relatively simple measures. For example, the Rathkerewwa Desiccated Coconut Mill in Sri Lanka was assisted under UNIDO's RECP programme to identify material efficiency measures. These included: laying rubber carpets on the floor of the loading bays, to avoid damage to coconuts during loading and unloading, which would cause them to be thrown away; awareness-raising among employees to avoid waste at the paring stage; reducing wash water; reusing coconut shells to fire the boiler. These measures enabled significant reductions of biomass wastage, and also saved energy. The combined measures provided savings of US$200,000 for an investment of less than US$5,000 (UNIDO, 2013).

Initiatives to gear **eating patterns towards healthier and less resource-intensive diets** are generally still at quite an early stage. Governments are often hesitant to address food consumption patterns explicitly, while many policies do in fact have an implicit effect on these patterns, such as tax and trade regimes, as well as agricultural policies. Some initiatives have been undertaken by NGOs, such as the LiveWell for LIFE campaign by the World Wildlife Fund, which is mainly targeted at countries within the EU.

Health, climate and land pressure issues can all be ameliorated by reducing the over-consumption of meat and excess calories more generally. Barriers to progress in this area are the preference and increasing ability of people to pay for meat-intensive diets; the low price of meat available through mass production; and general habits and cultural factors. However, a potential "win-win" is that less resource-intensive diets would in many cases have significant health benefits for the individuals concerned.

The provision of nutritional guidelines is a clear way of addressing this issue. For example, the official Nordic nutritional recommendations give strong guidance towards less meat-intensive diets, citing environmental arguments as well as health reasons (Fogelholm, 2013). There are also examples of voluntary awareness-raising schemes that aim to improve consumers' understanding of healthy diets e.g. the LiveWell for LIFE project (WWF and Friends of Europe, 2015). This makes suggestions for different healthy diet combinations, tailored to the cooking cultures of three countries: France, Spain and Sweden. As well as being nutritionally beneficial, it is calculated that these proposed country-specific "LiveWell Plates", if widely adopted, would cut GHGs from food supply chains by 25 percent by 2020. There is currently very little information about what, if any, impact such schemes have had. Nonetheless, there seems to be very substantial potential for improved health co-benefits from more resource-efficient diets. Other nations (e.g. Brazil, Qatar) have also developed dietary guidelines.

4.4. Overcoming barriers

In moving towards a healthier, resource-efficient food system, policy instruments are indispensable. States have powerful instruments, ranging from tax and trade regimes (including instruments such as water pricing), through to environmental policies (for example on fertilizer use and water pollution) and land tenure regulation. States can also provide an "enabling environment", for example by providing infrastructure and good education for boys and girls, and by fighting corruption. However, states cannot do this on their own. A promising route is to work in collaboration with the various "non-state" food system actors, ranging from individual farmers to large companies who actually manage and control resources. Multinational retailers and food companies are especially powerful, as they have significant control along the whole food chain, from primary production to consumption. They will however not automatically become agents of change for a more resource-efficient food system. Civil society groups and NGOs are also exerting increased influence on food systems (Schilpzand et al., 2010).

Delivering more resource-efficient food systems is largely dependent on providing the right incentives to various actors in the food system: farmers and fishermen, food processors, retailers and food service companies (restaurants, catering), and consumers. These incentives can come from politics (via policies: target setting, regulation, rethinking subsidies), from consumers (via value change: often related to personalized health concerns, broader feelings about "good" food and responsible lifestyles), as well as from civil society and NGOs. The importance of "soft" instruments, such as voluntary labelling schemes and other voluntary schemes, should not be under-estimated, as shown in Boxes 11 and 12.

At present, many of these incentives are not consistently pointing in the direction of more sustainable food production and consumption patterns: externalities are often unpriced, sometimes subsidies or tax exemptions are given for fossil fuels (fisheries and farming), certain agricultural sectors are protected, and consumers lack a clear insight into the environmental costs of food production. Farmers and fishermen have to produce in a very competitive market, in which typically only price matters. This implies that they do not receive an incentive from the value chain to apply more sustainable production patterns. The food supply-chain logic in affluent countries is largely aimed at a permanent and abundant supply, thus promoting food waste and unhealthy eating patterns.

While there are many options that would work in principle, collective action always poses a significant challenge. Industry would benefit from a clear "policy regime" that would make future expectations more predictable. "Soft" instruments such as voluntary agreements and round tables are ways to mutually create new

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

expectations. Food is a complex policy issue where many unintended policy effects are to be expected and the advances required are more likely to materialize if incumbent companies feel the competition of new entrants. This suggests that policy actors should ensure that their own environments are open to the ideas of "niche" players that may have the ideas to realize breakthrough innovations.

One way to enhance the "bite" of a policy regime on resource-efficient food systems may be to pursue a "nexus" approach and link with other, adjacent policy areas (FAO, 2014c, Kurian, 2016). In particular, the issues of health and well-being lend themselves to furthering the goals of resource efficiency and responsible production (Westhoek et al., 2014, Tilman and Clark, 2014), as many of the soaring public costs of health care are related to bad eating habits, which often happen to have an environmental impact as well.

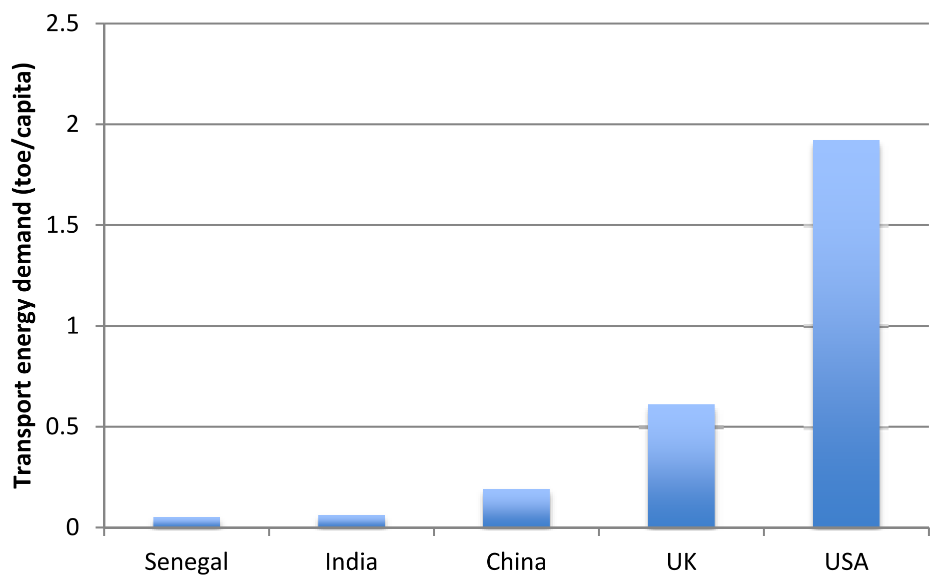
5. RESOURCE-EFFICIENT MOBILITY

5.1. Introduction: current status and trends in transportation demand

Globally, energy consumed directly by the transportation sector (including road, rail, air, water, and pipeline transportation) accounts for 19 percent of total primary energy supply (IEA, 2015, p. 33), and 64 percent of total oil consumption (IEA, 2015, p. 37). In addition, the infrastructure, vehicles, and their supply chains that facilitate transportation and fuel supply are major sources of energy and material consumption (UN Environment, 2010, p. 49, WSA, 2015, p. 2). Globally, transport energy use is dominated by the road transport sector (including passenger and freight transport) (IEA, 2009).

Transport demand per capita is currently unevenly distributed in global terms, as illustrated by Figure 70. With rising incomes, transport

Figure 70: Per capita final energy demand (tonnes of oil equivalent per capita) for transport in Senegal (0.05), India (0.06), China (0.19), the UK (0.61) and the USA (1.92)



Authors' own calculations, based on figures for Total Final Consumption (Transport) from "Balances", and for population from "Indicators", from IEA online statistics search (IEA, 2013b).

Part III: Increasing resource efficiency: best practices and case studies

demand per capita in emerging economies can be expected to move towards the levels of those in industrialized economies, causing significant impacts on global fuel demand and CO_2 emissions. One example of a recent growth trend for transport demand from non-OECD countries is illustrated by Figure 71, which compares passenger light-duty vehicle sales of OECD and non-OECD countries. The figure (up to 2010) suggests that non-OECD light-duty vehicle sales will by now have overtaken those of OECD countries (IEA, 2012a).

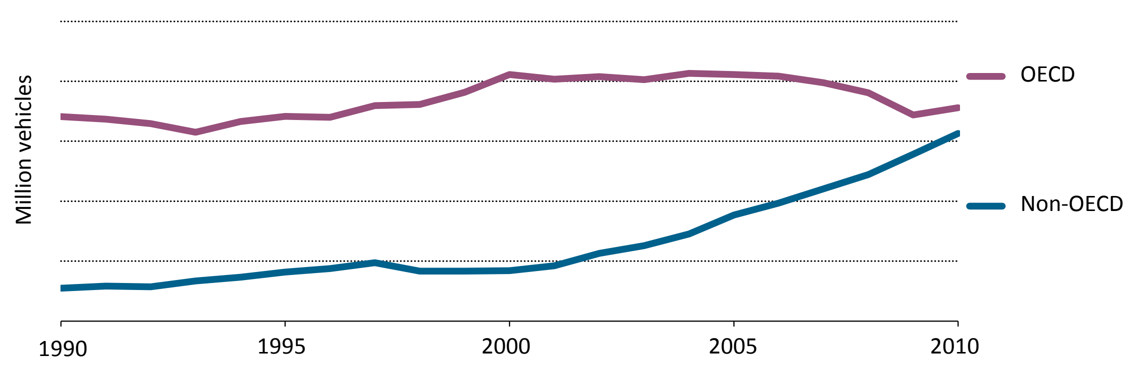
The potential global growth in transport demand therefore presents a major challenge in terms of the resources that will be required to meet this demand, and in the environmental impacts that will ensue from meeting this demand with current technologies. It is vital to find more efficient and less polluting means of delivering transport demand in order to avoid price spikes arising from resource constraints, climate change impacts arising from CO_2 emissions, and other environmental impacts.

The increasing efficiency of Internal Combustion Engine (ICE) vehicles, and the deployment of other efficient vehicle technologies such as Battery Electric Vehicles (BEVs) and Hybrid Electric Vehicles (HEVs), can limit the increase in transport energy consumption among industrialized nations, even while vehicle miles travelled (VMT) increase. For example, Figure 73 shows the case of the US, where motor gasoline consumption peaked in 2007 and has not yet increased beyond that level, while VMT steadily increased before and after the recent recession. This recent decoupling of VMT from gasoline consumption is suggestive of improvements in ICE vehicle efficiency, as well as possibly some transition to alternative technologies such as BEVs and HEVs.

On the other hand, the increase in transport demand among developing countries, where population and wealth are growing more rapidly, is expected to outpace improvements in fleet efficiency and decarbonization of transportation energy. This will result in significant increases in transport energy consumption (Figure 73).

The composition of transportation modes differs greatly among world regions (LTA, 2011, EPOMM, 2016). For example, 69 percent of road passenger journeys in Sydney are made by private transport, while 6 percent are taken by bus. By contrast, in Hong Kong, only 11 percent of passenger journeys use private transport, with 55 percent being made by buses

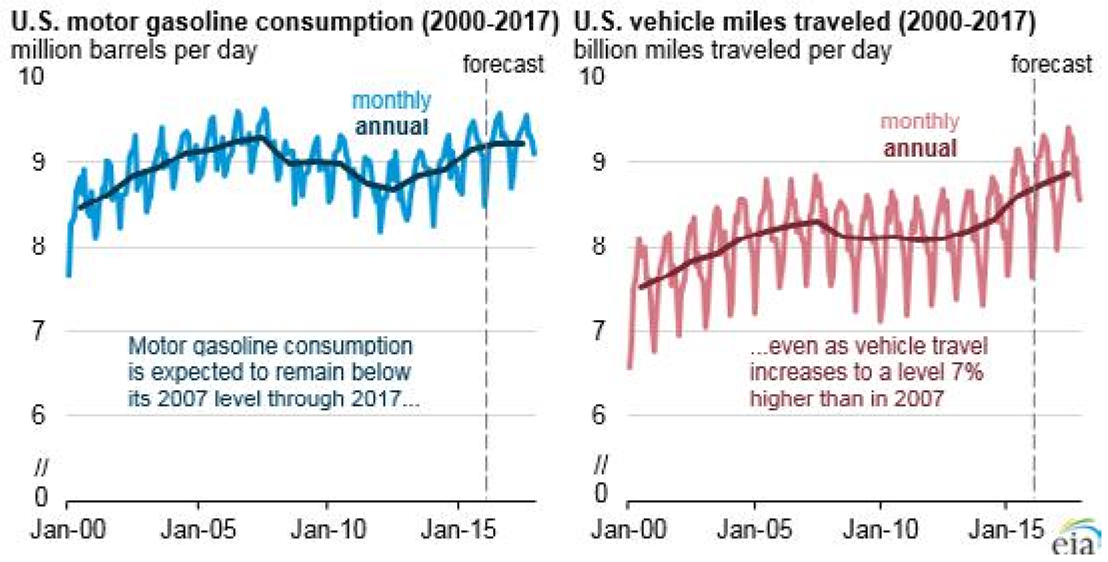
Figure 71: Passenger light-duty vehicle sales in OECD and non-OECD countries



Source: IEA, 2012a.

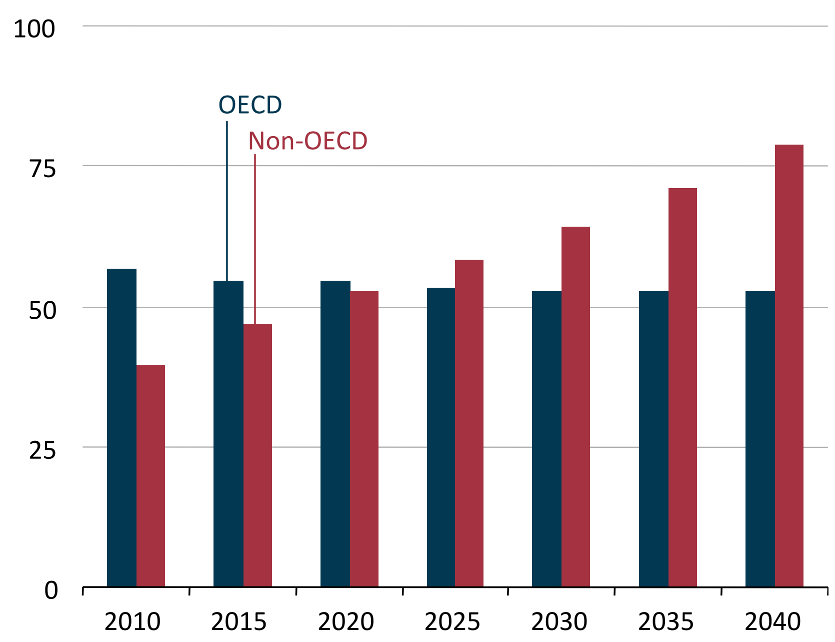
Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

Figure 72: Motor gasoline consumption and vehicle miles travelled (VMT) (2000–2017)



Source: EIA, 2016.

Figure 73: World transportation sector liquid fuel consumption (2010–2040) (in quadrillion Btu)



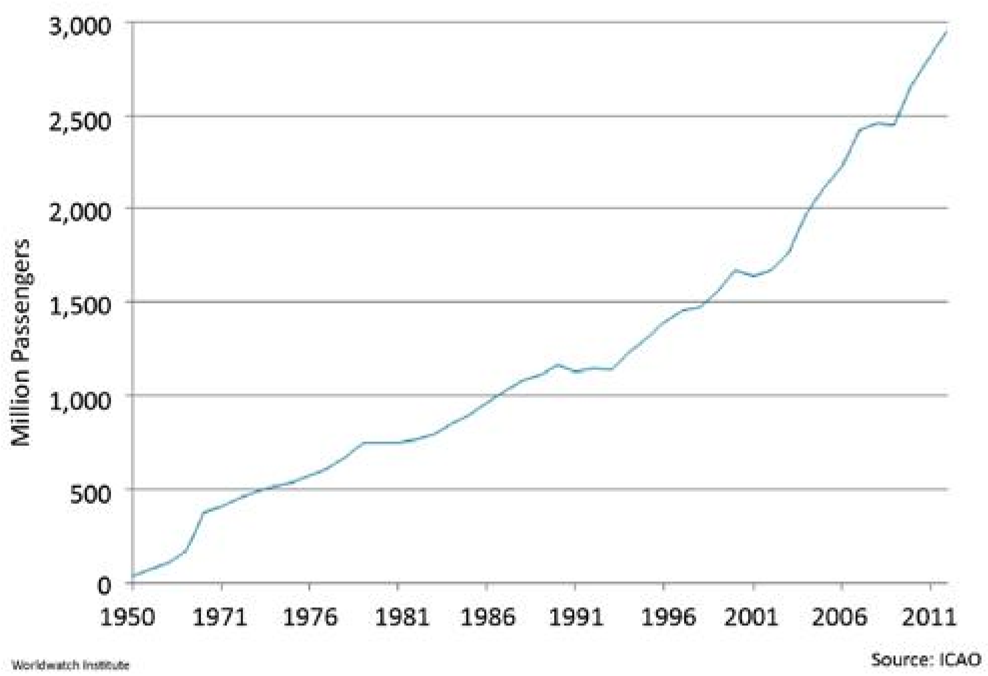
Source: EIA, 2013.

or trams (LTA, 2011). In general, however, the ownership of passenger vehicles is increasing sharply among developing countries, which could substantially increase the share of private transport in total transportation demand (OICA, 2016). In developing Asia (excluding Japan, South Korea and the Middle East), the motorization rate — measured by the number of vehicles per 1,000 inhabitants — more than doubled between 2005 and 2014. However, it remains at an average of 79 per 1,000 inhabitants, compared to 808 in the US (OICA, 2016).

As for air travel, passenger volume grew from about 1.7 billion passengers per year in 2001 to about 3 billion passengers per year in 2011 (Figure 74). At the same time, the fuel efficiency of passenger jets has also improved significantly. The amount of fuel consumed per air travel passenger almost halved between 1968 and 2015 (Figure 75). However, due to the rapid growth in air travel passenger volumes, the amount of energy consumed and GHG emissions generated from air travel have increased.

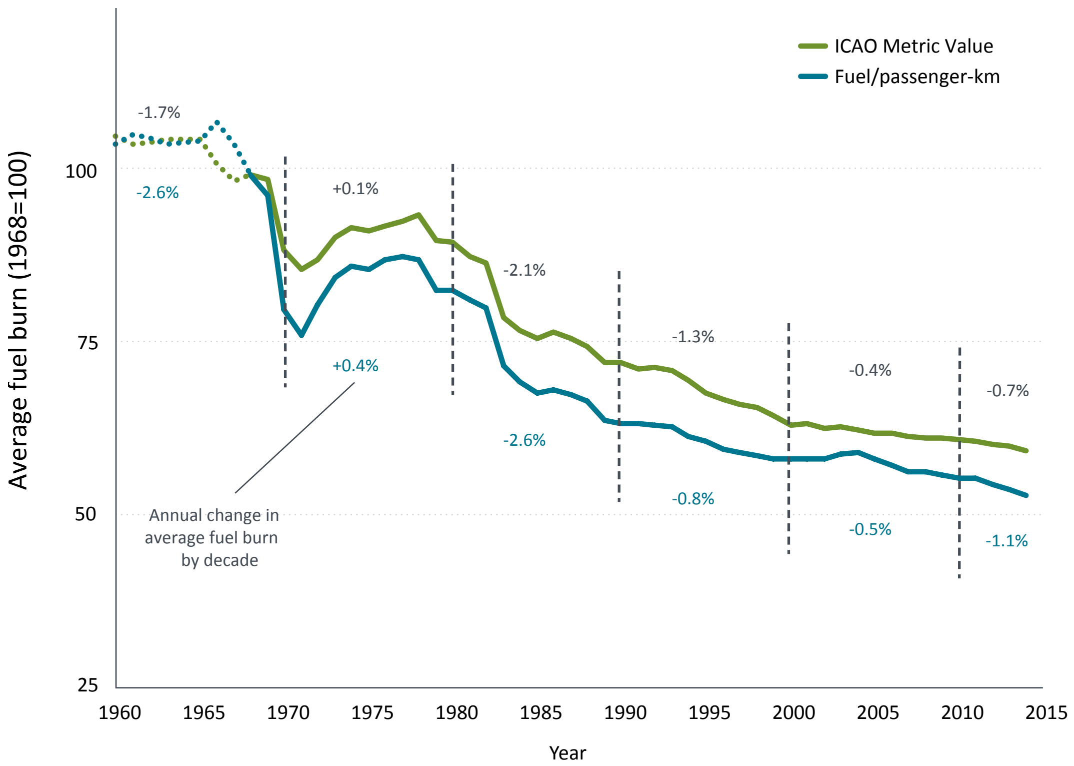
In the US, the demand for domestic as well as international freight transportation, including truck, rail, pipeline, and water transport, is increasing (Figure 76). Short-distance freight is dominated by trucks in the US, while rail and

Figure 74: World passenger air travel by volume, 1950–2012



Source: Renner, 2013.

Figure 75: Average fuel burn by commercial jet airplane (1960–2015)



Source: Kharina and Rutherford, 2015.

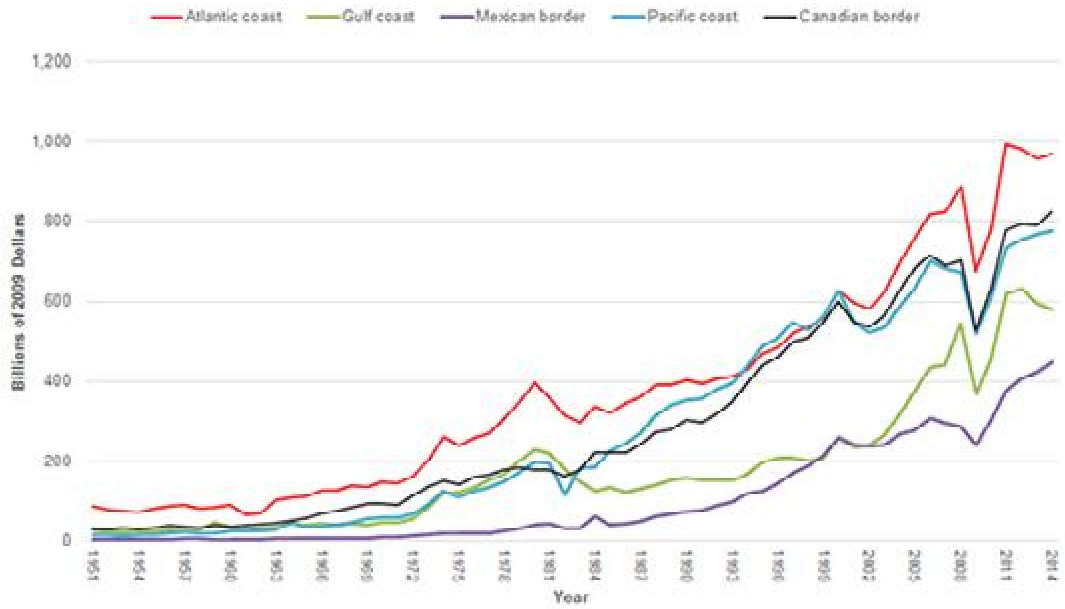
Note on Figure 11.6: The Fuel/passenger-km metric is as calculated by the International Council on Clean Transportation (ICCT), and is designed to measure the amount of fuel burned per passenger-km flown, "from the departure gate to arrival gate" (Kharina and Rutherford, 2015). The metric includes "all fuel consumed for taxi, takeoff, cruise, approach, and landing" (Kharina and Rutherford, 2015). The ICAO Metric Value was developed by the International Civil Aviation Organization (ICAO) to help establish a CO2 emissions standard for new aircraft. The main difference from the fuel/passenger-km metric is that the ICAO Metric Value (MV) "takes into account only the cruise performance and ignores other flight phases of an aircraft such as landing, takeoff, and climb" (Kharina and Rutherford, 2015). Although these omissions might be expected to lead the ICAO MV to estimate lower fuel burn than the ICCT's Fuel/passenger-km metric, Figure 11.6 shows the ICAO MV index higher for most of the period. Kharina and Rutherford (2015) suggest that this is most likely because the ICAO MV "is largely insensitive to change in aircraft structural efficiency, including the use of lightweight materials and design considerations, such as stretch and shrink aircraft", that lead to increased fuel efficiency on a passenger-km basis.

water transportation become more important as the transportation distance increases (Figure 77). Figure 78, which compares energy efficiency improvements between different transportation modes for the EU, suggests that while aircraft and passenger vehicles significantly improved their fuel efficiencies over the last decade, the efficiency improvements in freight during the same period were relatively small.

The IEA Energy Technology Perspectives 2012 describe a 2°C scenario (2DS), consistent with the goal of limiting global mean temperature increase to 2°C. This scenario requires a substantial contribution from the transport sector, with transport carbon emissions 50 percent lower than in a counter-factual 4°C scenario. Broadly, this requires an "Avoid/Shift/Improve philosophy": "avoid" implying "slowing travel growth via city

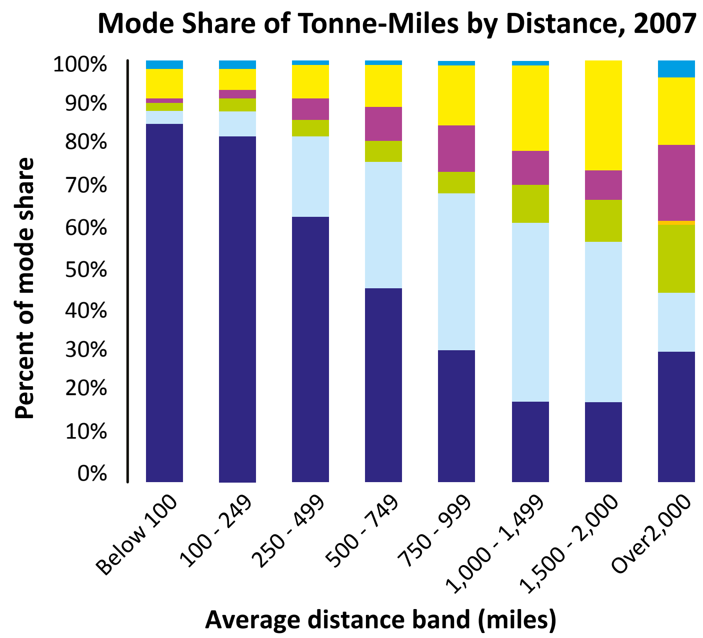
Part III: Increasing resource efficiency: best practices and case studies

Figure 76: Value of US international merchandise trade by coasts and borders 1951–2014



Source: DOT, 2015, p. 15.

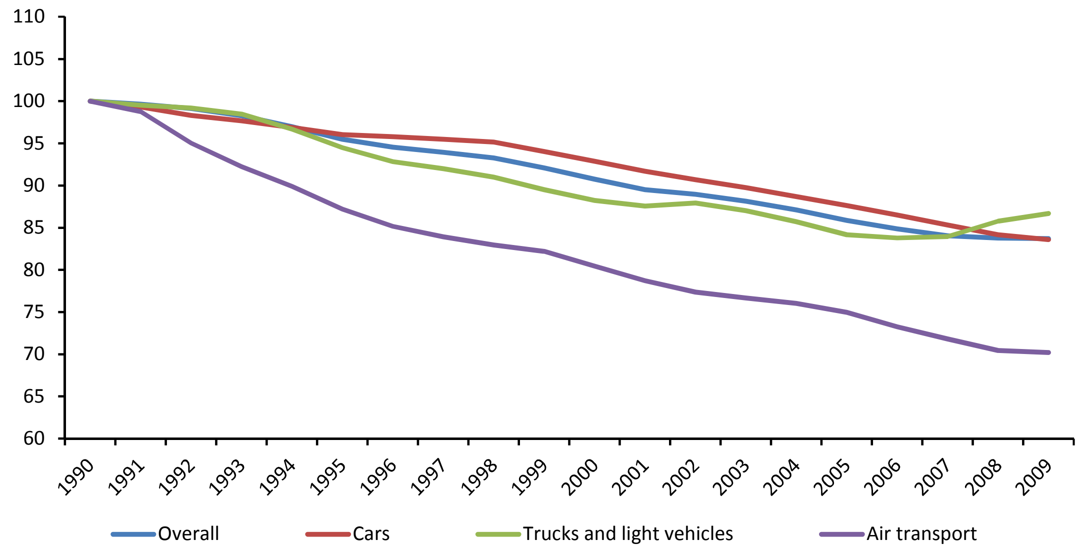
Figure 77: Modal composition of freight transportation by distance in the US



Source: DOT, 2015, p. 5.

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

Figure 78: Energy efficiency progress in transport in the EU



Source: Faberi et al., 2012.

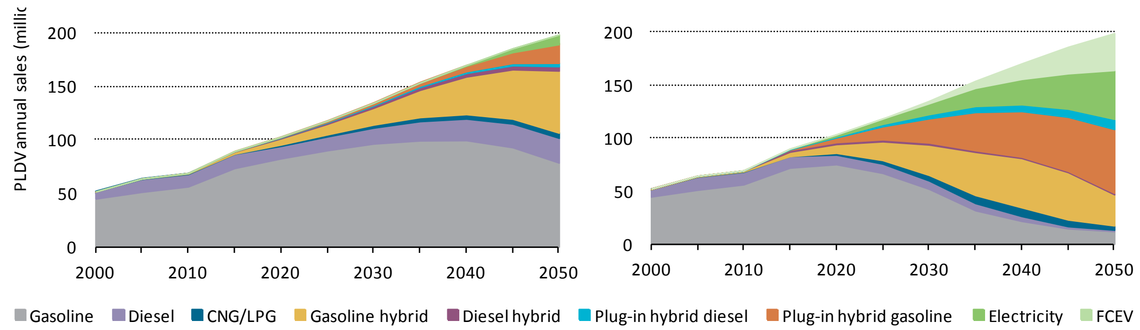
planning and demand management", "shift" involving "enabling people to shift some travel to transit, walking and cycling, and to shift goods from trucks to rail", and "improve" requiring "the adoption of new technologies and fuels" (IEA, 2012). Figure 79 shows the contribution of the "improve" — or technological change — strategy to the technology mix for passenger light-duty vehicles, compared with the counter-factual 4DS. As shown, the passenger light-duty vehicle mix in the 2DS sees a major technological shift towards electric, plug-in hybrid and fuel cell vehicles, which together constitute almost three quarters of sales in 2050. Figure 80 shows the passenger-kilometre demand reduction available from "avoid/shift" strategies, in large part due to the greater contribution of buses and trains, which (if fully loaded) have greater energy and GHG-efficiency than private cars.

This chapter continues by examining the potential for and implications of technological substitution ("improve"), and planning for demand reduction and mode-shifting ("avoid" and "shift"), in a resource-efficient and low-carbon transport future. Part III - Section 5.2 examines the life-cycle environmental and resource impacts of different technological, efficiency and modal-shifting transport strategies. Part III - Section 5.3 focuses on the "avoid" and "shift" strategies, considering how design and planning of urban infrastructure can be used to reduce transport fuel demand without adversely affecting the levels of comfort and access to services provided by transport.

5.2. Life-cycle analysis of transport technologies

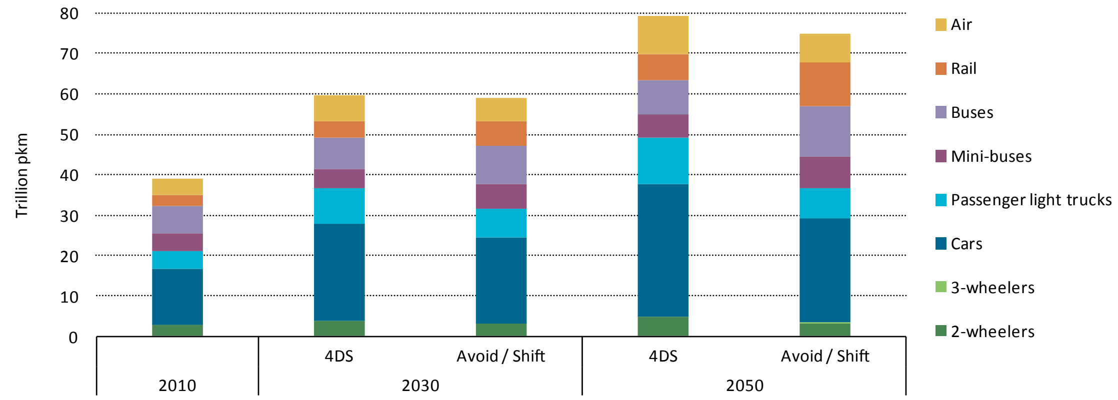
Changes in the transportation system have life-cycle environmental and resource impacts that are determined by multiple, interconnected factors. For on-road and air transportation, which are responsible for about 90 percent of the total transportation energy use, key factors include: (1) environmental and resource impact intensities of fuels; (2) fuel efficiency of fleet; (3) fleet-mix of mode; (4) modal-mix of transportation; (5) environmental and resource impacts of fleets and modes (upstream

Figure 79: Annual sales of passenger light-duty vehicles by technology in IEA 4DS, and under "improve" strategies



Source: IEA, 2012a.

Figure 80: Passenger-kilometre transport demand by mode in IEA 4DS, and under "avoid / shift" strategies



Source: IEA, 2012a.

supply chain, production, and end-of-life); (6) transportation demand per capita; (7) population and population density; (8) urban morphology; (9) type and level of transportation infrastructure demand; (10) environmental and resource impacts of transportation infrastructure; and (11) whether the changes in transportation system generate new demand, among others.

Life cycle assessment (LCA) helps examine the environmental and resource impacts of fuels, fleets and modes, and transportation infrastructure, which are (1), (5) and (10) above. In addition, full LCAs on transportation systems assemble these factors into environmental and resource impacts of a set of fuel, fleet, and transportation infrastructure choices.

5.2.1. Fuel and technology choice

The IEA 2DS focuses on the potential of technological substitution and demand reduction to reduce transport CO_2 emissions. The emission-reduction potential of any given transport technology and fuel combination is subject to some uncertainty and variation, due to the different life-cycle chains through which the fuels and technologies can be produced. It is therefore important to consider these possible variations in order to be aware of any risk of unintended consequences arising from a particular technology strategy.

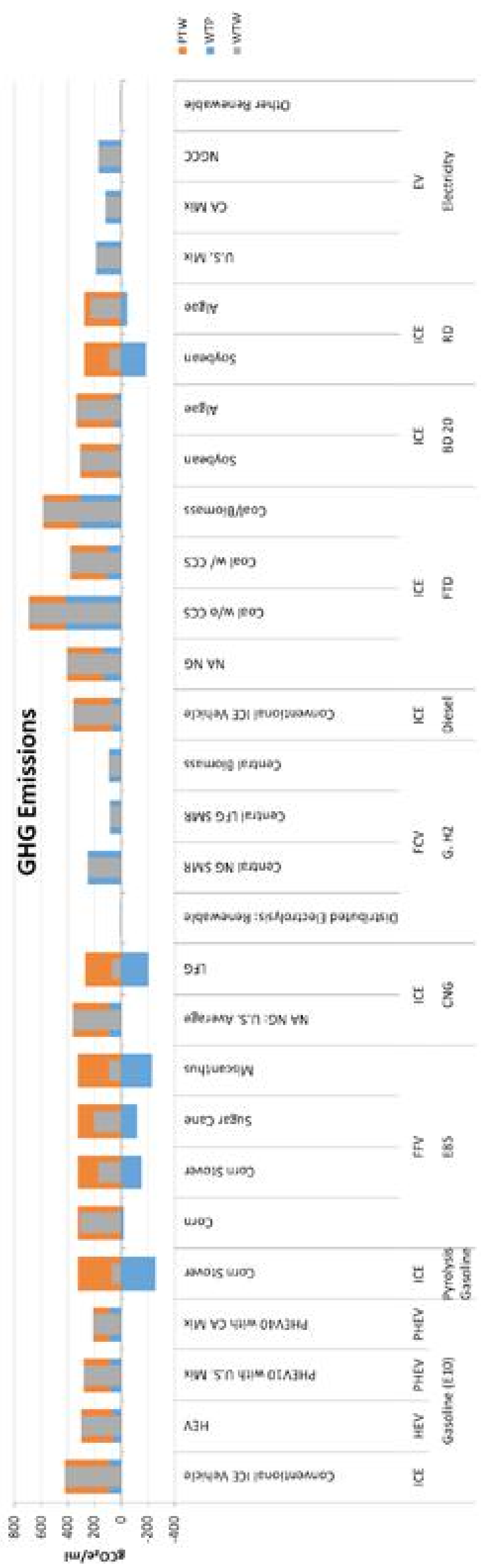
The natural resource and environmental implications of on-road vehicle-fuel combinations also vary significantly. The life-cycle energy impact of vehicle-fuel combinations of the future are described by Argonne's GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model (Argonne National Laboratory, 2014). This model has been developed to evaluate and compare the energy and environmental impacts of transportation fuels and advanced vehicles, by simulating the energy use and emissions output of various vehicle and fuel combinations. The entire life cycle — from well-to-wheels and from raw material mining to vehicle disposal — is taken into account. As shown in Figure 81, GHG emission intensity ranges from 700 to almost zero g CO_2e/mile.

Abbreviations:

ANL	Argonne National Laboratory
B20	20 percent BD Blend with LSD
BD	biodiesel
BPEV	battery-powered electric vehicle
CA Mix	California average electricity generation mix
CCS	Carbon Capture and Sequestration
CD	Charge Depletion operation of PHEV
CNG	compressed natural gas
CNGV	compressed natural gas vehicle
CS	Charge Sustaining operation of PHEV
CO_2e	CO_2 equivalent (i.e., amount of CO_2 emissions with equivalent global warming potential of emitted greenhouse gases)
COG	coke-oven gas
DI CI DV	direct-injection compression-ignition diesel vehicle
E85	a mixture of 85 percent ethanol and 15 percent gasoline (by volume)
EV	electric vehicle
FCV	fuel cell vehicle
FFV	flexible fuel vehicle
FTD	Fischer Tropsch Diesel
G.H2	gaseous hydrogen
gge	Gallons of Gasoline Equivalent (i.e. gallons of gasoline equivalent to the vehicle's energy use of the selected transportation fuel)
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation
GV	gasoline vehicle
HEV	hybrid electric vehicle
ICE	internal combustion engine
LFG	landfill gas
LNG	liquefied natural gas
LSD	low sulphur diesel
mi	miles travelled by the vehicle
NA	North America
NNA	Non-North America
NG	natural gas
NGCC	Natural Gas Combined Cycle
PHEV	plug-in hybrid electric vehicle
PTW	pump-to-wheels
RD	renewable diesel
SMR	Steam Methane Reforming
US Mix	United States average electricity generation mix
VMT	vehicle's mileage travelled
w/	with
w/o	without
WTP	well-to-pump
WTW	well-to-wheels

Figure 81 illustrates the GREET analysis for a range of vehicle-fuel combinations, with the aggregated "well-to-wheels" emissions in each case shown by the grey bar. As a point of reference, the emissions for a conventional ICE vehicle using petrol with 10 percent blended ethanol (E10) are shown on the far left, with well-to-wheel emissions of about 400g CO_2e/mile. Relatively few options, on a well-to-wheel basis, reduce CO_2e emissions to close to zero — the two closest options are vehicles fuelled by hydrogen produced by distributed electrolysis using renewably generated electricity, and electric vehicles that use a renewable source of electricity. Biofuels have a mixed performance, with well-to-wheel emissions varying greatly depending on the feedstock crop. For example, an 85 percent blend of corn-based ethanol (E85), on a well-to-wheels basis, has emissions comparable to a conventional diesel engine. E85 using sugar cane-derived ethanol has about half the well-to-wheels emissions of the conventional ICE engine with E10 blend. The more extensive well-to-wheel emissions reductions from the biofuel options are attributed to the "lignocellulosic" fuel chains, from miscanthus

Figure 81: Greenhouse gas emissions from well-to-pump (WTP), pump-to-wheels (PTW) and well-to-wheels (WTW) for vehicle-fuel combinations



Source: Argonne National Laboratory, 2014.

and corn stover (post-harvest maize residue). For electric vehicles, the well-to-wheel emissions depend largely on the fuel mix used to generate the electricity on which the car is powered: the figure shows that the well-to-wheels emissions of an electric vehicle, if the average carbon intensity of the current US grid is assumed, would be about half that of the conventional ICE with E10, or a similar level to an ICE fuelled by an E85 blend from sugar cane ethanol. EVs charged on California's grid mix compared to that of the US average would reduce well-to-wheel emissions by a greater amount.

Shiau et al. (2009) compared small and large-capacity PHEVs, HEVs, and conventional vehicles and found that for short trips and frequent charging, "small-capacity PHEVs are less expensive and release fewer GHGs than hybrid electric vehicles (HEVs) or conventional vehicles". This is due to the batteries required, which cause trade-offs between energy storage capacity and the vehicle weight, cost, and performance. These trade-offs are most pronounced in the urban environment, where the majority of trips cover short distances.

In the future, driverless vehicles or shared autonomous vehicles (SAVs) may be a significant disruptive innovation. However, we know very little about the impact of autonomous vehicles on VMT. Optimistic studies expect positive environmental effects, such as reduced parking and vehicle ownership needs, as well as a reduction in VMT and emissions, due to higher driving efficiency and increased sharing of vehicles (Anderson et al., 2016, Greenblatt and Saxena, 2015). Autonomous vehicles enable sharing of cars that otherwise stand still, leading to better use of the fleet and less material waste. Shaheen and Cohen (2013) found that members of car-sharing organizations decreased their VMT by 27 percent.

However, VMT could also increase when autonomous vehicles are implemented, for example by enabling populations who do not currently drive, such as senior citizens, to drive (Anderson et al., 2016), and from unoccupied rides to reach the next traveller. Fagnant and Kockelman (2014) model an increase in total travel of 11 percent. Therefore advanced vehicle technologies such as PHEVs and SAVs should be considered carefully.

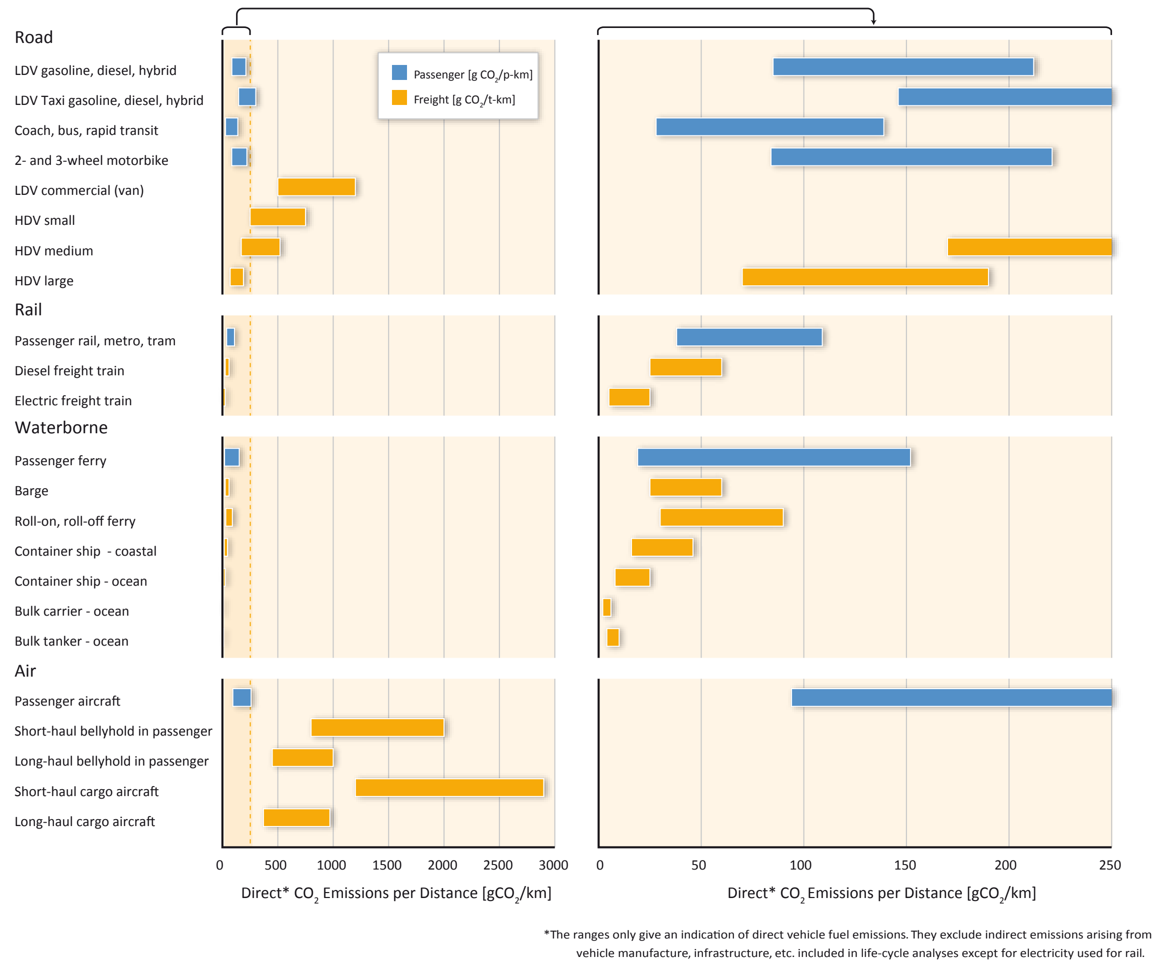
Thus, there are considerable variations in environmental impacts between different vehicle technologies and fuels, with a well-to-wheels analysis important to a full understanding of the impacts. On the other hand, many of the fleet-fuel combinations shown in Figure 81 have little to no market-share today, and average fleet- and fuel-mixes change relatively slowly due to the relatively long lifetime of fleets and the significant cost (sunken or new) of building fuel supply infrastructure.

5.2.2. Fleet and modal choice

Life-cycle environmental and resource impacts vary widely across different fleets and modes. In terms of direct emissions, passenger cars and passenger air transportation show generally higher CO_2 emissions per passenger-km than bus or rail (Figure 82). Among freight modes, CO_2 emissions intensity (measured as kg CO_2 per tonne-km) is highest among air transportation, followed by truck and water transportation (Figure 82).

In addition to the impacts directly generated during transportation, the impacts from the fuel cycle (WTP emissions in Figure 81), from vehicle manufacturing and disposal, and from the necessary infrastructure and its maintenance, should also be taken into account. In their comprehensive study, Chester and Horvath (2009) show that transportation infrastructure is responsible for a significant share of the total life-cycle energy consumption as well as GHG emissions across mode and fleet types, particularly for rail transportation infrastructure (Figure 83). For example, the analysis suggests that in the case of some rail networks, activities associated with constructing, operating and maintaining

Figure 82: Direct CO_2 emissions per passenger-km or tonne-km travelled by mode

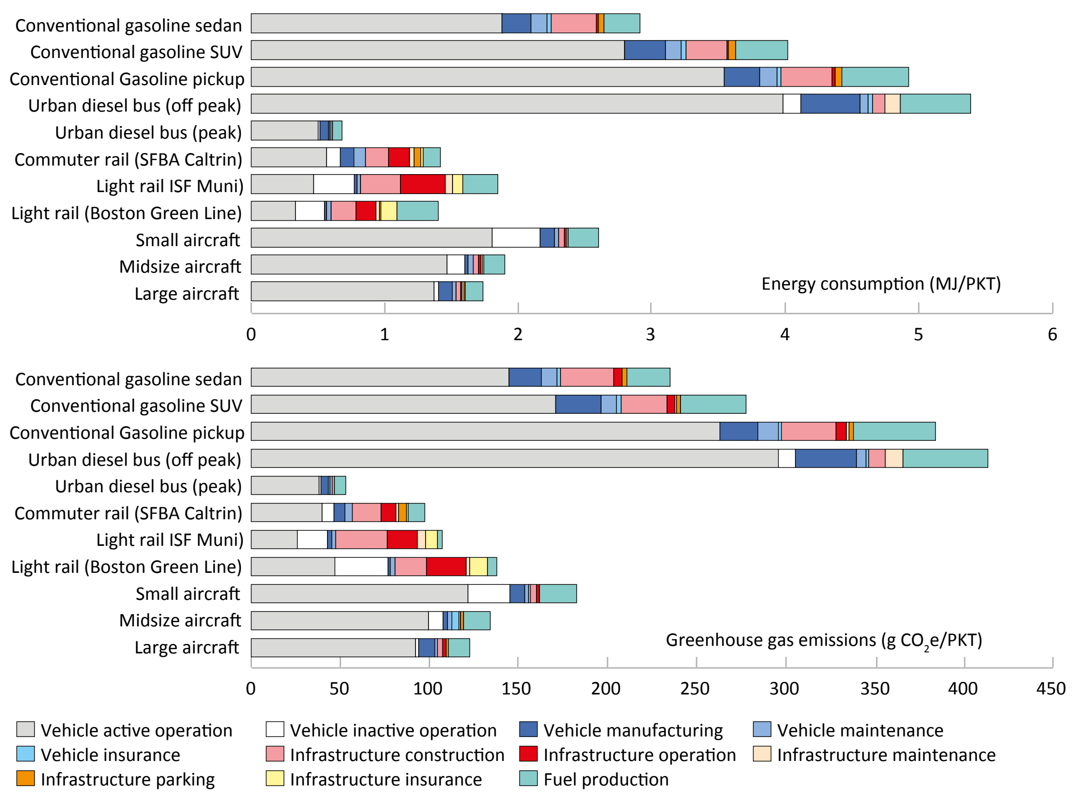


Source: IPCC, 2014b, p. 610.

supporting infrastructures could contribute to overall life-cycle GHG emissions per passenger-km similar to, or even greater than, that of large aircraft. Vehicle manufacturing contributes around 10 percent or less of the total energy consumption and GHG emissions across the fleets and modes considered (Chester and Horvath, 2009). Energy use and emissions per passenger-km in all modes are also highly sensitive to occupancy assumptions, considering which the authors note that "there are many different conditions under which modes can perform equally" (Chester and Horvath, 2009). The effect of occupancy assumptions can be seen for example by comparing the results shown in Figure 83 for an urban diesel bus at off-peak and peak usage times – the latter with markedly reduced life-cycle energy use and GHGs. This emphasizes the importance of ensuring that public transport modes enjoy high levels of use.

Modal shift from passenger cars to new public transportation systems such as bus rapid transit or rail involves varying levels of new investment to build infrastructure. This requires the use of resources and generates pollutants — upfront environmental and resource impacts that

Figure 83: Energy consumption and GHG emissions per passenger-km travelled



Source: Chester and Horvath (2009) p. 4.

can be "paid back", as long as the new public transportation infrastructure is sufficiently successful in displacing passenger car journeys. Thus, the environmental and resource performance of a new public transportation system depends on how much it displaces passenger car travel needs. It is also important to understand that modal shift from private vehicles to public transportation can rarely be done on the basis of a single mode, as door-to-door transportation generally involves multiple modes of transportation. Considering these aspects, Chester et al. (2013) show that, depending on the pollutant and the transit system in question, BRT and light rail transit (LRT) in the Los Angeles area would have to displace passenger vehicle travel needs by at least 1 percent to about 30 percent in order to realize any savings in life-cycle environmental emissions.

Another important consideration is whether the new transit system not only displaces existing transportation demand but also generates new demand that did not exist before. Miyoshi and Givoni (2013) for example, showed that 22 percent of the demand on the new High-Speed Train (HST) between London and Manchester would be newly generated demand. Furthermore, most of the modal shift to HST would come from existing railway transits, which is already efficient, thereby limiting the additional environmental benefits of HST.

More recently, Taptich et al. (2016) showed that GHG emissions can be reduced by fuel switching, modal shift, and fuel efficiency improvement in both passenger transportation and freight, while there are significant regional differences. In particular, as the fuel efficiency of vehicles improves, the benefits of modal shift become more marginal (Taptich et al., 2016). Furthermore, the analysis shows that the environmental performance of electrification depends largely on the vehicle types that it displaces and the background grid mix (Hawkins et al., 2013, Taptich et al., 2016). Focusing on freight in California, Nahlik et al. (2016) show that deep emission cuts are possible only when both fuel efficiency improvement, and rapid transition to low-carbon fleets such as hydrogen fuel cell and BEVs, are implemented in concert.

5.3. Urban systemic solutions to address transportation energy use in cities

5.3.1. Introduction

As identified by the IEA (2012a) and already explored in Part III - Chapter 3 and Section 5.1, the strategies of "avoiding" transport demand and "shifting" it onto alternative, less resource-intensive modes have strong potential to reduce resource consumption and the environmental impacts associated with transport. Pursuing each of these strategies requires a holistic approach to planning that coordinates transport infrastructure and the built environment to increase access to amenities and services (thereby avoiding transport demands) and access to public transport systems (thereby shifting transport demand from private transport onto shared transit). This section describes the relationship between land use and urban infrastructure, as it affects energy used in transportation.

A city's nominal average density — defined as the number of people per acre — is an important variable that shapes transportation demand, but is not the only key variable. Newman and Kenworthy (1989) show statistical evidence of a rapidly decreasing transport energy demand as city densities increase. More recent work has broken down the drivers of urban transport demand into a number of different variables, many of which may often be associated with denser urban forms, hence the apparent strong relationship between density and travel demand. However, the effect is not per se due to density alone, but due to the combination of these various associated factors, often referred to as the "five Ds".

Photo: ©UN Habitat / Julius Mwelu

5.3.2. The five Ds

Research conducted and summarized by the United States National Research Council (NRC) (2009) finds that five "Ds" are important in shaping energy use and transportation. These are:

- Density: Population density (people per square km) as well as activity density (people plus jobs per square km)
- Diversity of uses e.g. mixed residential–commercial
- Distance to public transit
- Design to support multiple modes of travel, including pedestrian, bicycle, automobile and public transit
- Destination accessibility, with a focus on job locations

The NRC conducted a meta-analysis of elasticity assessments of these five criteria. The elasticity quantifies the percentage change in VMT associated with a doubling (100 percent) in density and other "D" attributes. A summary of the NRC's analysis is reproduced in Table 9. It indicates that in the best case of all five Ds, a reduction of ≈25 percent in VMT can be expected based on US cities (NRC, 2009).

5.3.3. Urban planning in cities in developed countries

Table 9 addresses elasticities observed in already developed US cities, and indicates that there is a significant path dependency between land use and its impact on travel. Once urban sprawl begins, it is quite difficult to densify the entire city. As a result, densification efforts often focus on smaller pockets of the city, and those areas will see the benefit of the five Ds. In the US, these pockets are being developed around transit, termed transit-oriented developments (TODs). As noted in Part III - Chapter 3, TOD has been defined as "more compact development within easy walking distance of transit stations (typically half a mile) that contains a mix of uses such as housing, jobs, shops, restaurants and entertainment" (Reconnecting America, 2007). In 2004, more than 100 TODs were identified in the US, although not all of these were transit-friendly, for reasons such as the prevalence of free parking and the absence of good pavement connections. However, there is significant and detailed information about specific TOD projects in places such as Portland, Oregon, Arlington County in suburban Washington, D.C., and the San Francisco Bay Area, where a significant amount of travel behaviour data has been collected via resident

Table 9: Short-term elasticities of transportation demand

Elasticity	Value
VMT elasticity: best case synergy	25 percent
Individual elasticity:	
Density	5–12 percent
Diversity	5 percent
Design	3 percent
Accessibility to jobs	20 percent
Electricity demand elasticity with respect to price	−0.15 to −0.35 (for the Rocky Mountain region) (Bernstein and Griffin, 2005)

Source: NRC, 2009.

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

surveys (TCRP, 2008). The coming years should reveal how the emphasis on TODs in these US cities may help reduce VMT compared with the elasticities summarized above.

Housing density is an important factor in the effectiveness of TOD strategies, with higher densities being in general more advantageous in this regard. For example, public transit is effective in areas with above seven to 10 dwelling units (DU) per acre, or 2,315– 2,700 people per km² (The Louis Berger Group, 2004). Strategies such as car sharing (with traditional vehicles) require densities higher than 10 DU/acre. A density of 10 DU/acre — corresponding to buildings of about 4–5 stories — can thus be regarded as a threshold beyond which applying the five Ds can be expected to be most beneficial. 10 to 50 DU/acre is considered medium density in the US, and can be mapped visually to > 4 storey development. Therefore, the average VMT in the US is shown to be about 23 miles per person per day (Hillman and Ramaswami, 2010). In contrast, in New York City, which at 10,350 persons per km² (Kennedy et al., 2009) is far denser than the average US city, the personal VMT for a resident is about 9 miles per person per day.

It can be concluded that cities and neighbourhoods with densities lower than 7 DU/acre will struggle to reap the benefits of TOD strategies, and should therefore consider technological solutions. Furthermore, density alone is not sufficient: job-housing balance determines access to jobs, while mixed-use (diversity) and multimodal design support shorter trips being made by biking or pedestrian trips.

In large cities with extensive existing urban infrastructure, it can be difficult to implement the 5Ds extensively. Nonetheless, low-energy transport innovations are still possible. One such example is the concept of the bicycle-sharing scheme, which has now been developed in a number of cities in various countries. Though taking different forms, the essence of such schemes is to provide cheap, quick and spontaneous access to bicycles to cover short urban distances. A pioneering example of this is the Vélib' initiative in Paris, comprising a network of 1,200 automated hire points and a total of 20,000 bicycles across the city, available 24 hours a day. Users can pay on demand for a day or a week's access, or sign up for a longer subscription (UNIDO, 2013).

5.3.4. Urban planning in rapidly growing cities

Figure 70 above shows the low vehicle-kilometre demand in typical developing countries, compared with industrialized nations. However, rising wealth could substantially increase demand in emerging economies, as suggested by the strong increase in vehicle ownership in both India and China noted in Table 10. There is also a high level of inequality in the ownership of vehicles across these countries. As poorer countries become wealthier, if their cities are to be resource efficient, it is important that urban planning interventions are made early on, to ensure that their cities are not dominated by cars in the future.

Table 10: Vehicle ownership

Country	Vehicle ownership per 1,000 inhabitants (2013)	Increase (2012–2013)
China	91	15 percent
India	20	11 percent
US	790	0 percent
EU 15+EFTA	590	0 percent

Source: http://www.oica.net/wp-content/uploads//total-inuse-2013.pdf

The challenge in urban planning in such developing country scenarios is that the urban planning has to keep pace with rapid population growth. This has been highly challenging in cities all over the world, particularly in fast-growing cities. Master plans have to be made, within which microplanning is needed, so that peri-urban areas can be developed with appropriate transit and bus and road infrastructure. Larger cities such as Beijing, Guangzhao, and more recently Delhi, are experimenting with policies that limit driving and/or limit automobile ownership through a quota system. The city of Ahmedabad in India has used planning successfully to reduce VMT through mixed-use development (diversity), design (for multimodal transport), access to destinations, having a short distance to public transit, and more compact, higher-density development. This illustrates all the five Ds in a developing world setting. An important factor was the decision of the municipality to undertake its transportation planning alongside its broader Development Plan, and to give the resulting Integrated Mobility Plan a time-horizon of 20 years. This integrated plan therefore considered mobility in the context of high-density, mixed-use urban infrastructure. It chose to use all forms of transportation as complementary to each other, with local public transit systems connecting to mass transit systems at hub points. Dedicated walking and cycling lanes were also included alongside the BRT corridors (Swamy and Bhakuni, 2014).

Nevertheless, Cervero and Dai (2014) comment that more could be done in Ahmedabad to improve connections to the main BRT network from feeder systems, including pedestrian paths, cycle tracks and other transit modes. For example, while acknowledging that a large network of cycle tracks was built in conjunction with the BRT system, they comment that "for the most part, bike-paths run parallel rather than perpendicular to the busway, thus functioning more like competitive than complementary systems". Nonetheless efforts to integrate transport within sustainable urban planning approaches such as those undertaken in Ahmedabad are importantly and significantly moving in the right direction. Learning from their successes as well as their challenges will be important to take on board in many other fast-growing cities.

5.3.5. The land-use effect of transit

Density and transit provision influence each other. With transit most viable in higher-density areas, such transit can in turn further promote higher density along transit corridors: the advantages of access to transit create greater demand for homes along these corridors. This effect of transit on density is called the land-use effect of transit. Evidence suggests that "public transportation investments can, under the right circumstances, promote more compact development" (TCRP, 2015).

The land-use effect of transit should be distinguished from the ridership effects of transit (described in the previous section), which describes people choosing to take public transport instead of private vehicles for a given journey. The land-use effect suggests that well-designed transit investments can, by promoting higher-density settlements, help change the length of journeys required, and increase the number of shorter journeys that can be undertaken by bicycle or on foot.

Evidence from a recent TCRP report (2015) suggests that the indirect land-use benefits of transit may have a greater impact on reducing VMT than the direct ridership benefits. Key findings of the research are that the land-use impact of transit, by reducing the distances of some journeys, thereby making some car journeys shorter and enabling more to be undertaken on foot or by bicycle, could amount

Part III: Increasing resource efficiency: best practices and case studies
Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

to an 8 percent aggregate reduction in VMT. The impact of direct ridership effects of people taking public transport instead of their private car on a particular journey amount to an aggregate 2 percent reduction. Thus, the land-use effect appears to have four times the impact on VMT reduction as that of the ridership effect. The land-use effect may therefore be a highly significant component of the benefits of investments in transit. However, a sufficiently high density remains an important prerequisite for transit investments in the first place: as discussed above, a density of at least seven DU/acre seems to be required to render an initial transit investment viable.

5.4. Conclusions

Transport is a major global resource-consuming sector, with high environmental impacts. Global demand for transport services is expected to continue to rise, as the currently relatively low per capita transport demand of developing and emerging economies catches up with that of industrialized economies.

There are three main strategies for mitigating the rise in transport demand and associated environmental impacts: reducing transport demand; shifting demand onto more resource-efficient modes; and upgrading the transportation technologies themselves to be more efficient or less polluting. The first two options can make an important contribution to reducing transport energy demand and environmental impacts. These approaches require coordination and planning, as they will be optimized in residential built-up areas of medium to high density, areas characterized by mixed use, access to public transport and amenities, and designed to encourage multiple transport modes, including walking and cycling. In existing built-up cities, the potential for such design improvements may be limited by the lock-in created by pre-existing infrastructure. In contrast, an important and significant opportunity exists in rapidly growing cities and peri-urban areas in the developing world, where per capita transport demand may be expected to increase rapidly in the coming years. The principles of “transit-oriented development” represent a major opportunity in these cases, if they can be implemented before too much infrastructure creates lock-in to resource-inefficient transport practices.

While avoidance and shifting strategies are critically important to managing transport energy demand, it is also clear that a major improvement towards resource-efficient and low-carbon transport technologies is also required. Life-cycle analyses of the emissions and environmental impacts of technologies and fuel chains are crucial to supporting transport technology policies, as there are wide variations in the environmental impacts of different options. In particular, biofuel chains exhibit a large variation in well-to-wheel greenhouse gas emissions depending on the feedstock used, and the well-to-wheel emissions of electric vehicles are strongly dependent on the emissions intensity of the electricity grid on which the vehicles are charged (Figure 81). Alternative transport technologies may have other impacts, such as the significantly increased metal consumption associated with the production of electric vehicles compared with conventional ICEs. Other novel and emerging technologies may also entail some uncertainties in their impact and transport demand and hence upon resources. Driverless vehicles or shared autonomous vehicles (SAVs) may help reduce VMT and emissions through higher driving efficiency and increased sharing of vehicles. However, VMT could also increase as a result of providing car travel options to populations who do not currently drive, or due to unoccupied rides to reach the next traveller.

Such issues may not constitute a substantial enough concern to avoid the adoption of the new technology altogether. However, policymakers should monitor them to ensure that well-intentioned policy does not have counter-productive outcomes, such as, perhaps, shortages of critical materials or unplanned-for increases in VMT.

Part III: Increasing resource efficiency: best practices and case studies

6. RESOURCE-EFFICIENT ELECTRICITY SYSTEMS

6.1. Introduction

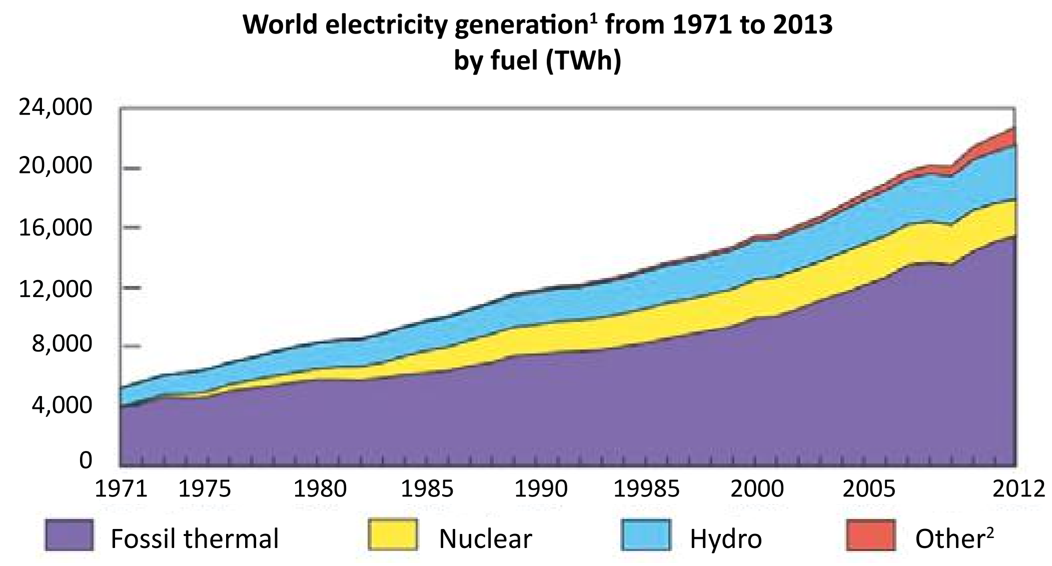
Electricity generation is a major consumer of resources and producer of environmental impacts, accounting for around 32 percent of total global fossil fuel use, and responsible for around 41 percent of total energy-related CO_2 emissions (IEA, 2010c). Almost 70 percent of electricity is generated from coal plants, with coal accounting for 73 percent of electricity sector CO_2 emissions (IEA, 2010c). The recent trend in electricity generation is one of rapid growth: global electricity generation grew by almost four times between 1971 and 2013 (Figure 84). It can be expected to continue to grow due to increasing demand for electrification. In the IEA’s 2010 Baseline scenario, global electricity production is projected to increase by 134 percent between 2007 and 2050 (IEA, 2010c).

However, the electricity sector also has huge potential to reduce its environmental impact due to the wide range of fossil-free electricity generation technologies available and in development. In national and global low-carbon scenarios, electricity often has a crucial role, decarbonizing first and fastest, and then expanding to replace other carbon-intensive vectors (e.g. in transport).

For example, in the IEA’s BLUE Map scenario, reported in Energy Technology Perspectives 2010 (2010c), by 2050 the carbon intensity of electricity has reduced by 90 percent compared with 2007 levels (from 507 gCO_2/kWh in 2007 to 67 gCO_2/kWh). Electricity becomes a critical vector for decarbonizing heat and transport, through technologies such as heat pumps and electric vehicles (IEA, 2010c).

Figure 85 shows the extent of increase in electricity demand in both the Baseline and BLUE Map scenarios, and the range of low-carbon

Figure 84: Historic trends in global electricity production

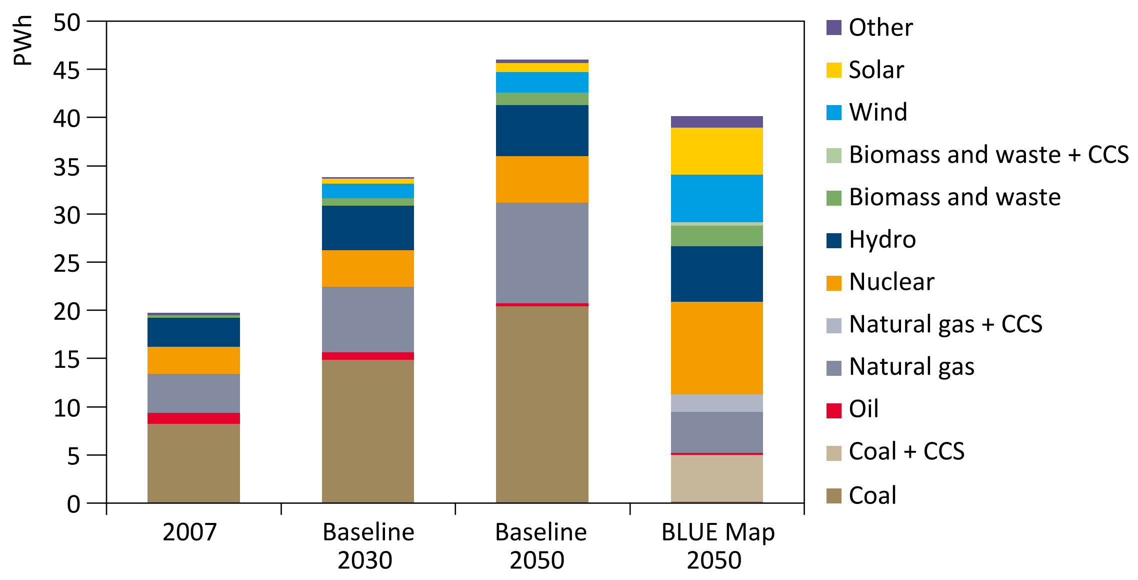


Notes: (1) Total world electricity generation excludes generation from pumped storage; (2) “Other” includes geothermal, solar, wind, heat, etc.

Source: IEA, 2015.

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

Figure 85: Global electricity production by energy source and by scenario



Note: Other includes electricity generation from geothermal and ocean technologies.

electricity generation technologies that are deployed in BLUE Map in 2050 in order to deliver the required emissions reductions. The figure also shows that, although both scenarios show a huge increase in electricity demand compared with 2007, the BLUE Map scenario has a 13 percent lower demand than the Baseline scenario. This is despite the fact that BLUE Map is supplying electricity for more uses, such as in heat pumps and electric vehicles, and is delivered through increased energy efficiency in buildings and industry (IEA, 2010c).

Renewable technologies face technical and market barriers. A long-term policy framework, as well as specific directed policy support measures, is likely to be needed to help power systems transition from fossil fuel to renewable generating sources. For example, in Germany in 2011, renewable sources made up about 22 percent of electricity generation, compared with around 7 percent in 2000, which constitutes a rapid increase. The main support mechanism for renewable electricity is the Renewable Energy Sources Act, which provides a feed-in tariff, differentiated by technology type, to renewable generators for a period of 20 years. The Act also establishes that renewable generators have priority access to the power grid (IEA, 2013a).

A key long-term overarching framework is the Energy Concept, unveiled in 2010, which "provides the long-term policy basis" to achieve the goal of energy system transition (BMWi, 2012). A 2012 amendment to the Renewable Energy Sources Act explicitly enshrines the renewable electricity targets of the Energy Concept in law. Thus, renewables must constitute the following share of German supply: at least 35 percent in 2020, 50 percent in 2030, 65 percent in 2040 and 80 percent in 2050 (IEA, 2013a).

One of the major barriers to increasing the penetration of renewable power is the engineering challenge of managing the variable output of wind plants. In view of this, another amendment to the Renewable Energy Sources

Act, the flexibility premium, has been introduced to encourage biogas-fired generating plants. These will be flexible enough to respond to fluctuations in the systems of other renewable generators, and be rewarded for doing so (IEA, 2013a).

In the UK, the target that national greenhouse gas emissions should be 80 percent below 1990 levels by 2050 is enshrined in national law (HM Parliament, 2008). To manage the intervening periods, a system of interim "carbon budgets" is used. Governments must set five-year successive carbon budgets, and the policies required to achieve them, each of which must be consistent with the longer term 2050 target. The Government is advised and monitored by an independent body, the Committee on Climate Change (CCC) (2014). Although the UK does not currently have a legally binding emissions target for the electricity sector, the CCC consistently advises on the importance of decarbonizing electricity as the most cost-effective route towards overall system decarbonization (CCC, 2013).

This chapter considers the resource efficiency issues and environmental impacts related to electricity generation. It first looks at the impacts of electricity generation, including both carbon-intensive and low-carbon options, and presents International Resource Panel analysis of the cumulative impacts of the two IEA scenarios summarized above: Baseline and BLUE Map. It then looks more generally at the importance of resource efficiency in the electricity sector. As a whole, the chapter will consider how material resource efficiency sits with decarbonization in the electricity sector; examining whether the objectives are complementary, or at times move in different directions.

6.2. Life-cycle impacts of electricity generation technologies

This section considers life-cycle impacts of the main groups of technologies that feature in IEA's BLUE Map and Baseline scenarios (as illustrated in Figure 85). It considers impacts under five categories: greenhouse gas emissions, human health impacts, impacts on ecosystems, material resource implications, and land occupation.

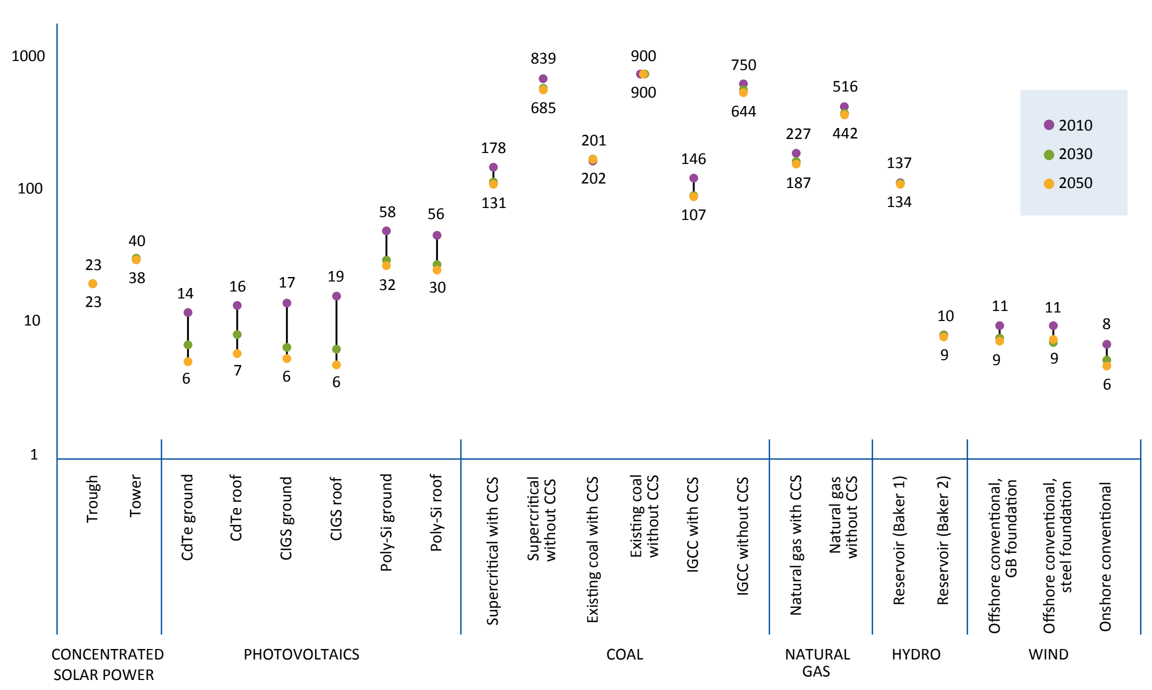
The assessments have been made on a life-cycle basis: they cover not only the emissions and impacts that occur on the site at which the electricity is generated, but also impacts arising from the construction of the generator and from any associated fuel supply chains. The impacts are compared per unit of delivered electrical energy: kilowatt-hour (kWh), megawatt-hour (MWh) or terawatt-hour (TWh). The analysis draws on the International Resource Panel's work on "Green Energy Choices" (UN Environment, 2015b), as well as additional sources.

6.2.1. Greenhouse gas emissions

When considered on a life-cycle basis, all electricity generation technologies are associated with some greenhouse gas emissions, as even renewable technologies require steel and concrete for their construction, the manufacture of which generates emissions. Figure 86 compares the life-cycle greenhouse gas emissions of various electricity generation technologies.

The figure shows that the highest life-cycle greenhouse gas emissions arise from coal-powered generation, at 750–900 gCO_2e/kWh. Meanwhile, the lower carbon content of methane reduces the life-cycle emissions of natural gas generation to around 500 gCO_2e/kWh. Carbon capture and storage (CCS) substantially reduces the emissions of coal- and gas-powered generation to around 150–200 gCO_2e/kWh. CCS has a capture efficiency of about 90 percent; in other words, 10 percent of the CO_2 produced in combustion is still released into the atmosphere. These residual emissions mean that on-site combustion remains the biggest contributor to life-cycle GHG emissions for CCS plants.

Figure 86: Life-cycle GHG emissions of different electricity generation technologies, in gCO_2e/kWh



The numbers for future years reflect a reduction of emissions expected due to technical progress and the reduced emissions in the production of the equipment following the implementation of a mitigation scenario.

Source: UNEP, 2015b.

Renewables remain the lowest GHG-emitting technologies of those surveyed in Figure 86, even including all life-cycle emissions, with most being clustered in the range of 10-20 gCO_2e/kWh. Wind turbines achieve the lowest life-cycle GHG emissions; despite requiring substantial amounts of steel and cement, they have an energy payback time of around four months. Slightly higher estimates of 40–60 gCO_2e/kWh are given for some types of solar PV and concentrated solar power, due to the greater energy intensity of materials and manufacture. Hydropower plants exhibit significant variation in life-cycle GHG emissions. One of the uncertainties is the rate of biogenic CO_2 and methane emissions of hydropower reservoirs, with some reservoirs by contrast even showing a net uptake of CO_2. The hydropower life-cycle inventories (LCIs) in the UN Environment (2015b, 2016b) study are based on two proposed reservoir hydropower plants in Chile. The variation between the GHG emissions results for the two cases shown in Figure 86 is mainly due to the difference in emissions levels associated with transportation for constructing, operating and maintaining different facilities. As one of the case-study plants would have been situated in a very remote location, the transportation of construction materials to the site makes a significant contribution to its calculated life-cycle GHG emissions. The comparison of these two cases indicates that the material and energy required to construct hydropower plants is very site-specific (UN Environment, 2016b).

Not included in Figure 86 are technologies such as biomass and nuclear power generation. Meta-analyses of LCA studies indicate that life-cycle GHG emissions of nuclear are likely to be in a similar region to those of most of the renewables. Weisser (2007) reports a range from reviewed studies of 2.8–24 gCO_2e/kWh, and van der Zwaan (2013) found a similar range of 5–17 gCO_2e/kWh, with a central value of 10 gCO_2e/kWh. Sovacool (2008) found a minimum value of 1.36 gCO_2e/kWh, but a much higher maximum value of 288.25 gCO_2e/kWh, and a mean of 66.08 gCO_2e/kWh.

Part III - Chapter 5 discussed life-cycle GHG emissions for different biomass-based transport fuel chains, and found that these emissions vary widely depending on the feedstock and conversion process used. Similarly, the use of biomass as a fuel for electricity generation can also vary widely, depending on the crop that is grown, how it is harvested, stored and transported to the power station. Thornley et al. (2015) carried out a life-cycle analysis of a number of different biomass energy chains, including two biomass-to-electricity chains: a small-scale gasification/combustion plant using wood chips from locally grown energy crops; and a large-scale combustion-only power plant using forest residues from North America, imported by ship to the UK. They found that the small-scale gasification plant using local energy crops had life-cycle GHG emissions of 60 gCO_2e/kWh, compared with 55 gCO_2e/kWh for the large-scale plant using imported forest residues.

In another paper, Röder et al. (2015) examine two biomass-to-electricity chains, one using forest residues, the other sawmill residues. In both cases the residues were collected from forestry industries in South-Eastern United States, and shipped to the UK for power generation. The baseline LCA GHG results for these chains were 132 gCO_2e/kWh for forest residues and 140 gCO_2e/kWh for sawmill residues, with the transportation stages of the supply chains being responsible for the largest emissions share (39 percent for forest and 36 percent for sawmill residues). However, sensitivity analyses showed potential for substantial variation. The baseline cases assume that the fuel used to dry the feedstock is biomass. However, if the drying fuel switched to diesel — as might happen if the market drives up the value of the biomass — emissions would rise to 271 gCO_2e/kWh for forest residues and 279 gCO_2e/kWh for sawmill residues. Another source of significant variation is the length of time that the biomass is stored at the pellet mill, as biomass in storage generates methane emissions. One month of storage increases the baseline emissions for forest residues from 132 gCO_2e/kWh to 317 gCO_2e/kWh. After two months, emissions rise to 489 gCO_2e/kWh; after three months to 670 gCO_2e/kWh; and after four months to 862 gCO_2e/kWh, which begins to be in the emissions range of current unabated coal generation. An even greater sensitivity to storage time is observed in the case of sawmill residues, for which emissions reach the range of unabated coal after only three months of storage.

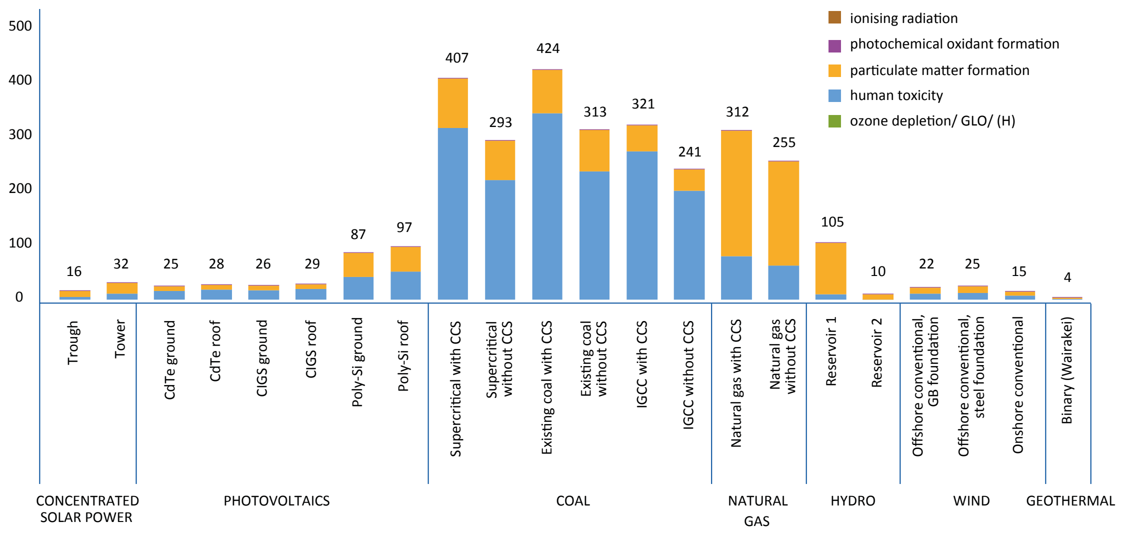
There is not scope in the current study for an extensive literature review of LCAs of biomass-to-electricity chains. However, the contrasting results and sensitivities from just two studies of fairly similar supply chains emphasize the complexities involved. Although it seems that in some circumstances, biomass electricity generation can produce substantial greenhouse gas reductions compared with coal and gas generation, there is substantial potential for variation, including counter-productive results. This underlines the importance of LCAs in informing the selection of biomass-to-electricity chains, and in informing policy.

6.2.2. Human health impacts

Figure 87 illustrates the International Resource Panel's assessment of human health impacts from life-cycle analyses of selected electricity generation technologies (UN Environment, 2015b). The figure shows that the main human health impacts from electricity generation technologies come from particulate matter formation and toxic emissions, and that these are in general much greater in the combustion-based coal and gas generation technologies.

CCS has little effect in reducing the particulate emissions of coal and gas plants, with estimates ranging from a 10 percent reduction to a 20 percent increase. Estimated increases are due to the reduced energy efficiency of the CCS process, and emissions arising from the manufacture of the CCS components and infrastructure (Singh et al., 2011, Koornneef et al., 2012).

Figure 87: Human health impact in disability adjusted life years (DALY) per unit of electricity generated (kWh) of selected electricity generation technologies



Source: UNEP (2015b), Figure 2.

Toxic effects are especially high in coal technologies due to the toxic effects of metal leaching from mines, which occurs regardless of whether or not CCS is applied at the power station. CCS may also introduce more toxic risks, as solvents used in the capture process, degradation products and compounds released during capture can all have toxic effects. However, the International Resource Panel notes that "there is still a degree of technological uncertainty about the exact CCS solutions to be implemented and an insufficient understanding of emissions, reactions and toxicity of the chemicals involved" (UN Environment, 2015b).

For wind, the areas covered by wind farms have some use restrictions due to safety precautions and noise. Reservoir hydropower can create human health impacts, as the creation of large bodies of still water can provide habitats conducive to disease vectors for malaria, river blindness, dengue or yellow fever (Kumar et al., 2011, Ziegler et al., 2013). Standing water can also create anoxic zones leading to the release of mercury bound in soil, leading to toxic effects in humans (Driscoll et al., 2013, Gump et al., 2012, Kumar et al., 2011). The difference between the human health impacts found for the two hydro projects analysed in the LCI, as shown in Figure 87, emphasizes the site-specific nature of hydropower impacts. Run-of-river hydro — typically on a much smaller scale — would be likely to avoid some of the above-mentioned human health impacts, because it does not require the creation of a large body of standing water.

The nuclear fuel chain causes some emissions of radionuclides, with the largest impacts from the mining of uranium and concerns about the safety of long-term storage of spent fuel. There is also a security concern over the potential for accidents, as demonstrated by Fukushima and Chernobyl, and the proliferation of nuclear weapons. The potential health impacts from the regular operations of the nuclear power plants are small compared to those from fossil power. The impact of nuclear accidents is potentially larger, comparable to that of coal mining accidents, but less frequent. Dones et al. (2004) highlight concerns around long-term emissions of radioactive substances from tailing ponds, mining sites, plant operation and waste disposal. Another evidence review finds that "there are still considerable uncertainties related to the transfers of radionuclides, including the impact of low doses to large populations over long periods of time, and how to appraise the risks associated with low-probability, high consequence disasters" (Agnolucci et al., 2015).

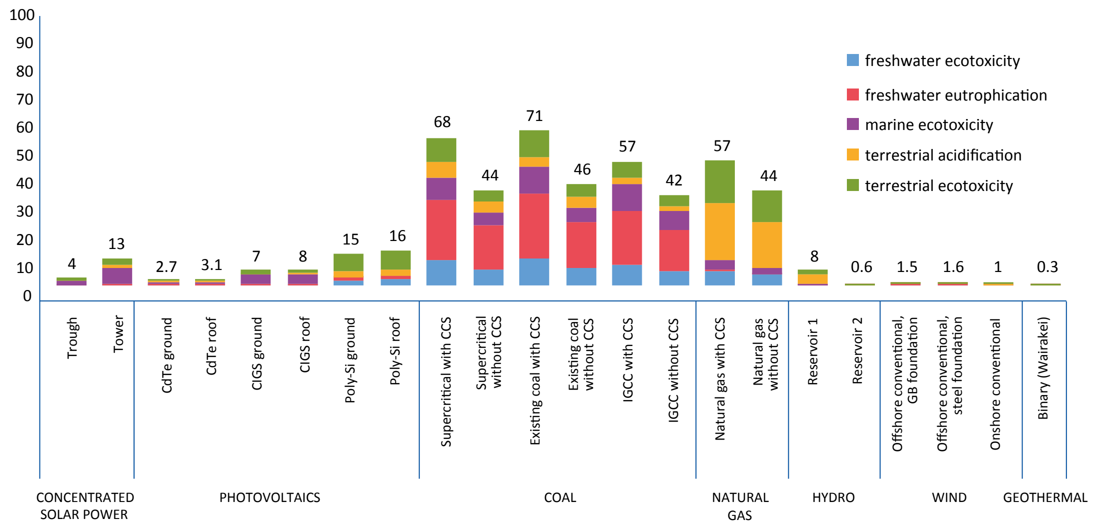
There are also potential concerns about the combustion of biomass. In a fairly specific example, Sarigiannis et al. (2015) argue that a shift from the use of oil to biomass for space heating in several metropolitan areas of Greece has led to increased particulate matter concentrations, and quantifiable human health impacts. More generally, Porter et al. (2015) suggest that "many of the most popular candidates for bioenergy crop feedstocks are high-emitters of isoprene, monoterpenes, and other biogenic volatile organic compounds (BVOCs), precursors of surface-level ozone (O3) and fine particulate matter (PM2.5)". They further argue for the importance of comparing the potential impacts of different types of bioenergy crops, "since the differences between the highest and lowest emitting candidate crops are large: eucalyptus and other woody energy crops rank among the highest of known BVOC emitters […] while rapidly growing cellulosic alternatives such as switchgrass (*Panicum sp.*) and Miscanthus (*Miscanthus x Giganteus*) are among the lowest".

6.2.3. Impacts on ecosystems

Figure 88 illustrates the International Resource Panel's analysis of ecosystem impacts of the selected electricity generation technologies.

Ecosystem impacts can arise from increases in atmospheric nitrogen and the increased mobilization of phosphorus, which contribute

Figure 88: Ecosystem impacts in species-years affected per TWh of electricity following different damage pathways



Source: UNEP, 2015b.

to eutrophication; as well as emissions of eco-toxic, acidifying pollutants or other organic chemicals that have local or global impacts (UN Environment, 2015b). Fossil fuel mining and combustion are major sources of these pollutants. Fossil fuel extraction technology has improved substantially, allowing access to vast resources that were previously considered technically challenging or uneconomic (Rogner et al., 2012). A continued expansion of fossil fuel use, however, would not only aggravate pollution-related environmental problems, but also result in impacts on habitat for species, as coal mines and gas rigs expanded to new areas (UN Environment, 2015b). One important concern is combustion, which oxidizes sulphur contained in the fuel and nitrogen contained in the air, leading to their emission to air. It also volatilizes and distributes mercury, a toxic metal of substantial concern to ecosystems. Another important concern is water and soil pollution resulting from coal mining, ash handling, and shale gas production.

As well as fossil fuel mining and combustion, impacts also arise from the mining and production of metals and cement that are also required for the construction of non-fossil power plants. This emphasizes the importance of LCA to ensure that the impacts of alternative generation types are fully accounted for.

Figure 88 shows that, although ecosystem impacts do arise from non-fossil fuel sources, the impacts are considerably lower than those attributed to fossil fuel generators. Hydropower dams can cause substantial water use and affect ecosystems in adverse ways, through migration barriers, habitat fragmentation and change, and changes in flooding regimes and nutrient transport. Hydro reservoirs can increase sedimentation, which increases flood risk (Xu, 2002), as well as increasing the organic content of the reservoir water, creating anoxic zones which lead to increased methane formation as organic matter decays (Kumar et al., 2011, UN Environment, 2016b). Reduced sediment flow can also create negative impacts downstream due to the reduced delivery of nutrients, and increased vulnerability to erosion (UN Environment, 2015b, Kumar et al., 2011). The

Part III: Increasing resource efficiency: best practices and case studies

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

transition from a shallow fast-flowing river to a lake-type environment is a major habitat change which, while beneficial for some species, may not allow the survival of others (UN Environment, 2016b, Kumar et al., 2011). Dams can also create fragmentation within habitats, reducing genetic exchange and connectivity between ecosystems (Finer et al., 2012), as well as obstructing the pathways of migratory fish species (Pess et al., 2008) (Thorstad et al., 2008, UN Environment, 2016b).

Careful project selection and design may be able to mitigate such impacts. For example, design measures can facilitate fish migration, both through gateways built into dams (Wollebaek et al., 2011), and through improved turbine design (Deng et al., 2010). Adjusting the flow-operation of the dam in "environmental flow" regimes can substantially reduce ecosystem impacts, with only a relatively small impact on power production (Guo et al., 2011, Esselman and Opperman, 2010). Constructing or enhancing habitats in nearby areas can replace the types of shallow water habitats that would otherwise be lost as a result of the dam construction (UN Environment, 2016b).

As the above discussion demonstrates, large-scale reservoir-based hydro projects can have a large impact concentrated on their immediate vicinity. Some analyses suggest that smaller-scale and run-of-river hydro may have lower environmental externalities (Sheldon et al., 2015), although these too create environmental impacts. Other analyses suggest that when impacts are expressed per unit of energy delivered, it is by no means clear that small-scale hydro has lower externalities than large-scale hydro (Bakken et al., 2012, Kumar and Katoch, 2016). As context is crucial, impacts should be considered on a site-specific basis (Botelho et al., 2016). The balance between considering impacts in relation to other technologies on a normalized per-kWh basis, compared with the specific local impacts of the project in question on its environment, must also be weighed up.

Photo: ©oonat

There are some concerns over the impact of wind power on habitat for certain species, and especially over birds and bats colliding with rotor blades. Site selection and operational adjustments can limit the number of bird and bat fatalities (Arvesen et al., 2015).

As in the previous category, CCS does not mitigate ecosystem impacts — in fact, it seems to slightly increase them. This is attributed to the requirement for additional equipment and infrastructure, the use of amine-based solvents in some of the systems which leads to ammonia emissions causing eutrophication, and the fact that the reduced efficiency of the plant increases the emissions per unit of electricity of pollutants that cause acidification and eutrophication.

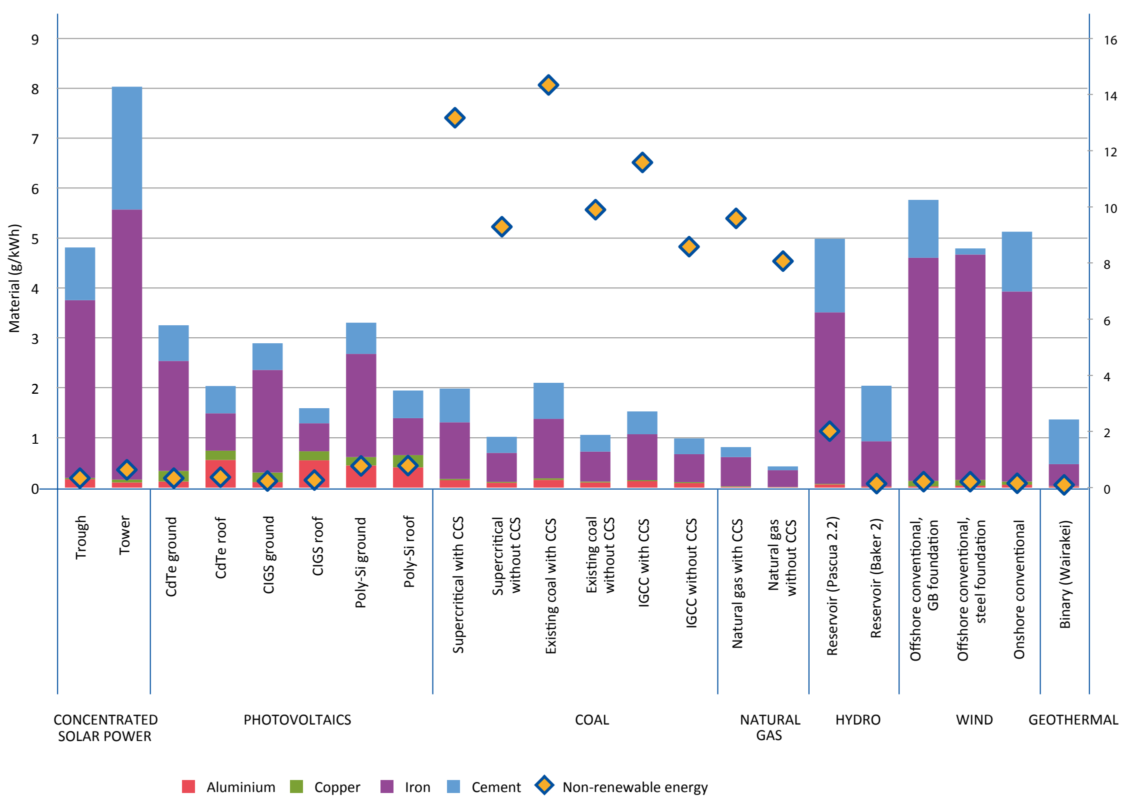
Little literature has been found on the ecosystem impacts of nuclear power. However, Vandenhove et al. (2013) report on an environmental risk assessment of the impact of radioactive discharges from Belgian nuclear plants. They conclude that "the current discharge limits for the Belgian [nuclear power plants] considered do not result in significant risks to the aquatic and terrestrial environment and that the actual discharges, which are a fraction of the release limits, are unlikely to harm the environment".

On biomass, Lovett et al. (2015) developed a framework for assessing ecosystem impacts of energy provision, and applied it to the specific case of the production and combustion life cycle of UK-produced short rotation coppice (SRC) and miscanthus. Discussing their review of papers on ecosystem impacts, they highlight that some have investigated the potential of SRC for bioremediation, including of landfill leachate, municipal wastewater and brownfield sites contaminated by metals and arsenic, with both positive and negative findings. Other reviewed research reported on potential benefits of SRC and miscanthus to birds, invertebrates and other wildlife.

6.2.4. Resource implications

Figure 89 shows the resource requirements of the selected electricity generation technologies. In all cases, these are dominated by the iron and cement required for their manufacture. Renewables have a consistently larger material resource impact than fossil fuel technologies. However, the requirement of the fossil fuel technologies for non-renewable energy is evidently much larger, as also indicated in the figure.

Figure 89: Bulk material and non-renewable energy requirements per unit power produced



Fossil technologies have high cumulative non-renewable energy demand, but low bulk material requirements.

Source: UNEP, 2015b.

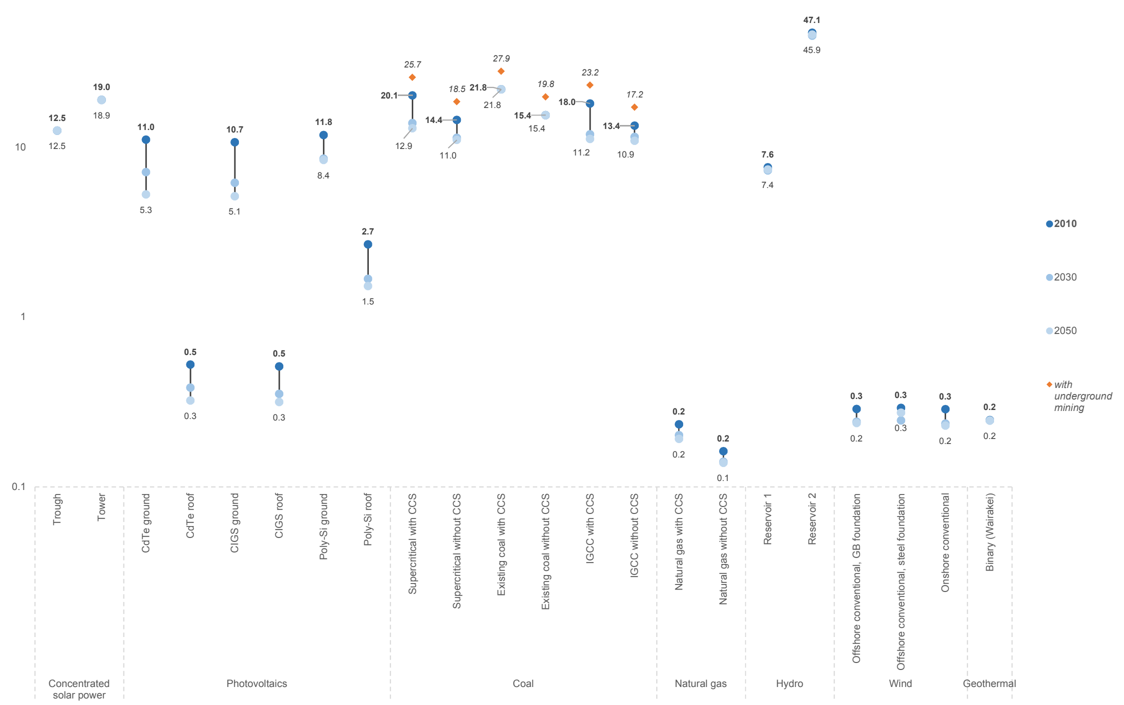
6.2.5. Land occupation

Figure 90 compares the total land occupation attributable to the selected technologies reviewed by UN Environment (2016b).

Coal-fired power generation has high land-use impacts, dominated by the indirect land-use effects associated with coal mining. Surface mines have high land-surface occupation, while underground mines also have high land use, due to the timber required to provide underground supports and infrastructure inside the mine. In contrast, the land-use impact of solar technologies — photovoltaics and concentrated solar power — is dominated by direct land use, i.e. the space occupied by the plant itself.

Roof-mounted PV systems have a much lower land-use impact, as the analysis assumes that the space taken on the roof of a pre-existing building does not constitute additional land use. The figures for wind account for the land occupation of the wind turbines and associated infrastructure, which is very small. However, due to spacing between the turbines, the land occupation of a whole wind farm would be much larger, in the range of 100m²a/MWh. This figure is relevant as the presence of a wind farm restricts some forms of land use, although the land between the turbines can normally still be used for agriculture, or left to wildlife. The land occupancy of reservoir hydro is similar to coal, due to the large land-use impacts of the reservoir.

Figure 90: Comparison of the impact on land occupation in terms of m² per MWh/a of electricity production from different technology sources, in Europe, in 2010



Note on figure: Land occupation is measured in square metre-annum (m²a) per MWh electricity produced, i.e. one square metre occupied over a year per MWh, or one square metre for producing one MWh per year. For coal, the red diamonds signify the land occupation associated with underground mining.

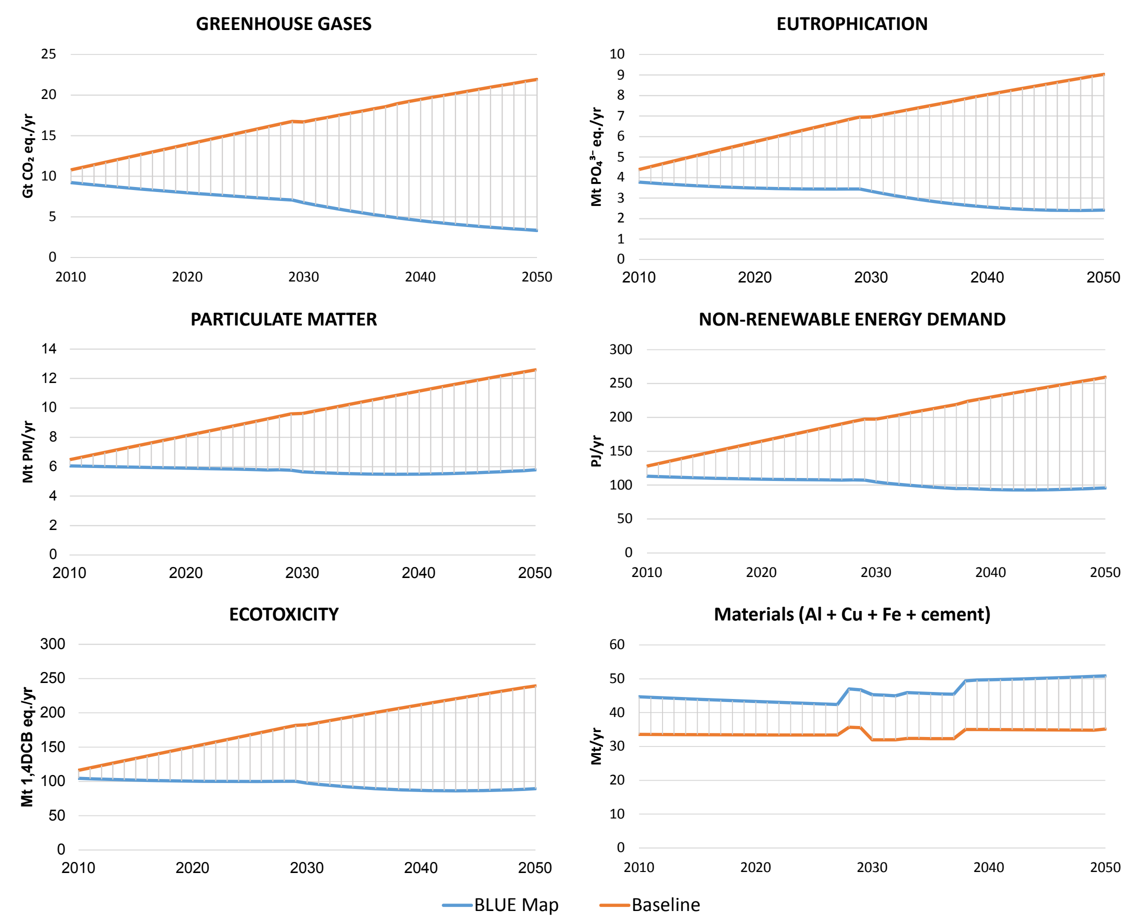
Source: UNEP, 2016b.

6.2.6. Future scenarios

The International Resource Panel has analysed the combined impact of these different technology types, by comparing the impacts under a range of indicators of the BLUE Map and Baseline scenarios from the IEA's Energy Technology Perspectives 2010 (IEA, 2010c). The results of this analysis are shown in Figure 91.

As shown in Figure 91, the impacts in terms of eutrophication, particulate matter, non-renewable energy demand and ecotoxicity are all substantially lower in the BLUE Map scenario than in the Baseline scenario. In other words, ambitions to reduce impacts in these categories would largely be consistent with the ambition to substantially reduce greenhouse gas emissions. The exception is in materials demand, which sees a greater demand for aluminium, copper, iron and cement in the BLUE Map scenario than in the Baseline scenario. This increased material demand occurs as a result of the need for new low-carbon technologies and infrastructure. As suggested by Figure 89, these technologies frequently have a higher material footprint per

Figure 91: A comparison of environmental pressures caused by pollution and resource pressures resulting from two different electricity scenarios, the IEA Baseline scenario, indicating a continuation of present development, and the IEA BLUE Map scenario, reflecting aggressive efforts to reduce greenhouse gas emissions



Source: UNEP, 2015b.

unit of final energy delivered than equivalent fossil-fuel-powered technologies. However, International Resource Panel analysis suggests that "responding to the world's energy needs in 2050 (as per the IEA's BLUE Map scenario) would only require one year of current global production of iron and two years of current global copper production" (UN Environment, 2015b).

6.3. Resource efficiency aspects of electricity supply and demand

This section now considers the electricity system from a resource efficiency perspective, examining the demand side, the supply side and the overall operation and management of the system. It considers how attention to resource efficiency in the electricity sector interacts with and supports the goal of decarbonization.

6.3.1. Resource-efficient electricity demand

As discussed in Part III - Section 6.1, many low-carbon scenarios see a growing demand for electricity. This is due to both the increasing uptake of electrical technologies in emerging economies, and also electricity becoming a crucial low-carbon vector for the decarbonization of an increasing range of demands, such as transport and heat (IEA, 2010c). This growth in electricity demand presents a major challenge for a supply system that is simultaneously undergoing a major transition towards low-carbon technologies. In this context, demand-side efficiency improvements have a critical role to play in reducing the challenge faced by the supply side of the system, making the overall low-carbon transition more feasible and more affordable.

Improvements in the efficiency of the building stock contribute to a reduction in electricity demand, as well as heating fuels. Ventilation and cooling in buildings is typically provided by electricity, though heating often by other fuels. However, decarbonization of the heat supply may involve increasing electrification. Dobbs et al.'s (2011) analysis has improved heating and cooling performance in buildings, accounting for 12 percent of the total resource productivity benefits they identify.

Improved lighting can account for 6 percent of McKinsey's total identified resource efficiency benefits. Options include "upgrading lighting to light-emitting diodes (LEDs), retrofitting commercial lighting controls, and replacing inefficient white goods and home and office electronics" (Dobbs et al., 2011, p. 90). As discussed in Part III - Chapter 3, smart control of lighting technologies in buildings and on streets could save energy by reducing the amount of time that they are unnecessarily turned on.

6.3.2. Resource-efficient electricity generation

Although scenarios such as IEA's BLUE Map envision a major transition to low-carbon generation sources, the number of coal and gas plants will increase substantially over the coming decades. McKinsey estimates that in 2030, nearly one third of coal plants will still be using the less-efficient subcritical technology, and half of gas plants will still be using basic gas turbines, rather than combined cycle. In China, for example, more than 80 percent of coal plants are subcritical, with an average efficiency of 34 percent, compared with a Canadian average of 41 percent (Dobbs et al., 2011). McKinsey estimates that China will build 550 GW of new coal capacity between 2010 and 2030. There is significant potential for resource efficiency gains and reduced pollution if the coal and gas plants built globally in the coming can be raised to the most advanced designs.

In conventional large-scale thermal power plants, the typical electrical efficiency of 30–40 percent implies that 60–70 percent of the energy in the fuel is lost as waste heat. If this waste heat can be recaptured and put to another use, this very substantially raises the overall efficiency of the plant. So-called "combined heat and power" or "cogeneration" plants are established technologies that exist in various locations, providing heat to industrial, commercial or residential users. This of course requires come

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

kind of heat distribution infrastructure, or "district heating network" of well-insulated hot water pipes. For example, McKinsey notes that "in Denmark, district heating covers more than 60 percent of space heating and water heating requirements", and that in 2007, 80 percent of this heat came from combined heat and power plants (Dobbs et al., 2011). However, in places without a district heating network infrastructure, the use of heat from power stations can be limited by the lack of available customers. Furthermore, there may be barriers to investment in new district heating infrastructure due to upfront capital costs, and the embeddedness of existing infrastructures and heating supply systems.

In the case of CCS, it could be argued that there is a conflict between resource efficiency and decarbonization: as noted above, the capture process draws energy from the plant, making the conversion of fuel to electricity less efficient. If there was a major concern about the global availability of coal, this could lead to a serious criticism of CCS being an inefficient use of scarce and valuable resources. However, the major driver for CCS is precisely that the global supply of fossil fuels far exceeds the capacity of the biosphere to safely absorb the CO_2 that would result from burning it (McGlade and Ekins, 2015). Hence the technical reduced efficiency of CCS is not of sufficient concern to override the potential decarbonization benefits.

6.3.3. Resource-efficient system planning

As well as the technical efficiencies of particular supply and demand technologies, the overall efficiency of an electricity system is affected by its overall planning and operation, on both temporal and spatial dimensions.

6.3.3.1. Temporal

Traditionally, electricity systems are coordinated such that the sum output of generators is at any time sufficient to whatever demand users collectively place upon it. This has tended to promote a mix of generation technologies, ranging from "baseload" generators that operate almost continuously with restricted ability to adjust themselves to follow demands; to slightly more flexible "mid-merit" plants that can operate a more variable schedule based on predicting times of greater demand; and highly flexible "peaking" plants, whose output can be ramped up very quickly in order to meet the "spikes" of peak demand, which are typically fairly brief. Essentially, this model is based on an assumption of a relatively inflexible demand side, and a highly flexible and responsive supply side. It entails maintaining many plants that are used fairly infrequently, and some for only a handful of hours per year, within the overall fleet of generation plants.

In order to reduce GHG emissions from power generation, many countries intend to introduce large quantities of renewables into their power systems. However, the generation profiles of renewable technologies can be highly variable, and they do not necessarily provide a perfect match for demand profiles. For example, wind speed may drop at the time of peak electricity demand, causing wind-power output to fall. The probability with which variable renewables can be expected to provide power output at the time that it is needed is a crucial issue for their successful integration within power systems. One measure of this is known as the "capacity credit", which expresses the amount of conventional capacity that a given renewable technology is able to displace without reducing system reliability, as a percentage of the peak-rated installed capacity of the renewable technology. The higher the capacity credit, the more reliably the renewable output coincides with demand, and the more conventional plant can be displaced (i.e. retired, or not commissioned) as a result.

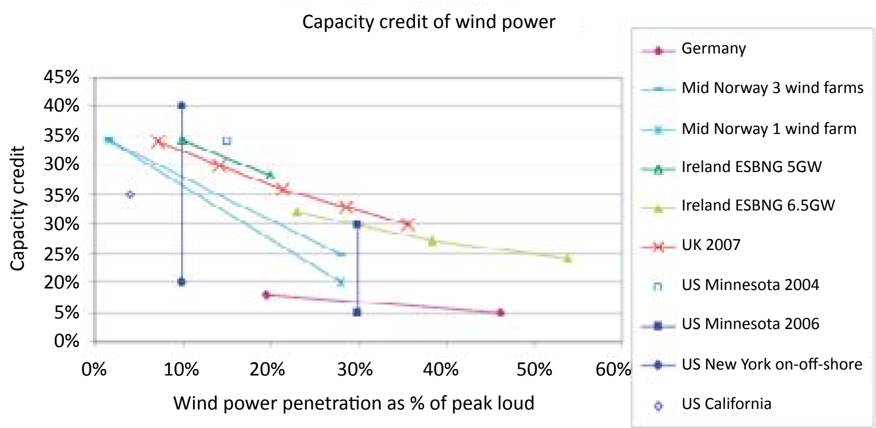
Factors affecting the capacity credit of a renewable technology include the typical output profile of the renewable resource, and how well this matches the system demand profile; whether the system is isolated or well interconnected with other systems that can offer buffering of peaks

or troughs in renewable output; and whether the system is endowed with flexible fast-response renewable technologies such as large-scale reservoir hydro. As a result, the capacity credit of any given renewable technology differs according to the system into which it is being introduced. Holttinen et al. (2009) examine the estimated capacity credit of wind in studies of a number of different systems, at different levels of wind-power penetration, as shown in Figure 92. At low levels of wind penetration, the authors report that the capacity credit in all of the systems shown is similar to what the average output of the wind turbines would be as a percentage of their peak output (capacity factor). However, as wind penetration increases, its capacity credit drops. This is because a greater total amount of wind means greater variability, which (all else being equal) must be covered by flexible conventional plant. As a result, a doubling of wind capacity does not double the amount of conventional plant that can be retired or not built, as more capacity needs to be kept on standby — hence the declining capacity credit.

Ueckerdt et al. (2015) analyse capacity credits for solar and wind systems in Indiana (US) and Germany, as shown in Figure 93. They note that the capacity credit for solar is much higher than for wind in Indiana, because peak demand in this system occurs during summer daytimes, due to air-conditioning load, which evidently has a strong correlation with solar output. By contrast, peak demand in Germany occurs during winter evenings, to which solar PV can make no contribution. Hence in this system, wind generally has a higher capacity credit, albeit much lower than PV's initial capacity credit in Indiana, because wind output in Germany is not as strongly correlated to peak power demand as solar PV output is in Indiana (see lower two panels of Figure 93). Ueckerdt et al. also note that optimizing the relative penetrations of wind and solar in either system would enable a higher overall capacity credit of the variable renewables in combination (see upper two panels of Figure 93). However, in both systems and for both technologies, the clear decline in capacity credit as renewable penetration increases can be seen.

As noted, the capacity credit measure describes the amount of conventional plant that a unit of renewable capacity can displace for a given

Figure 92: Capacity credit of wind power, results from eight studies

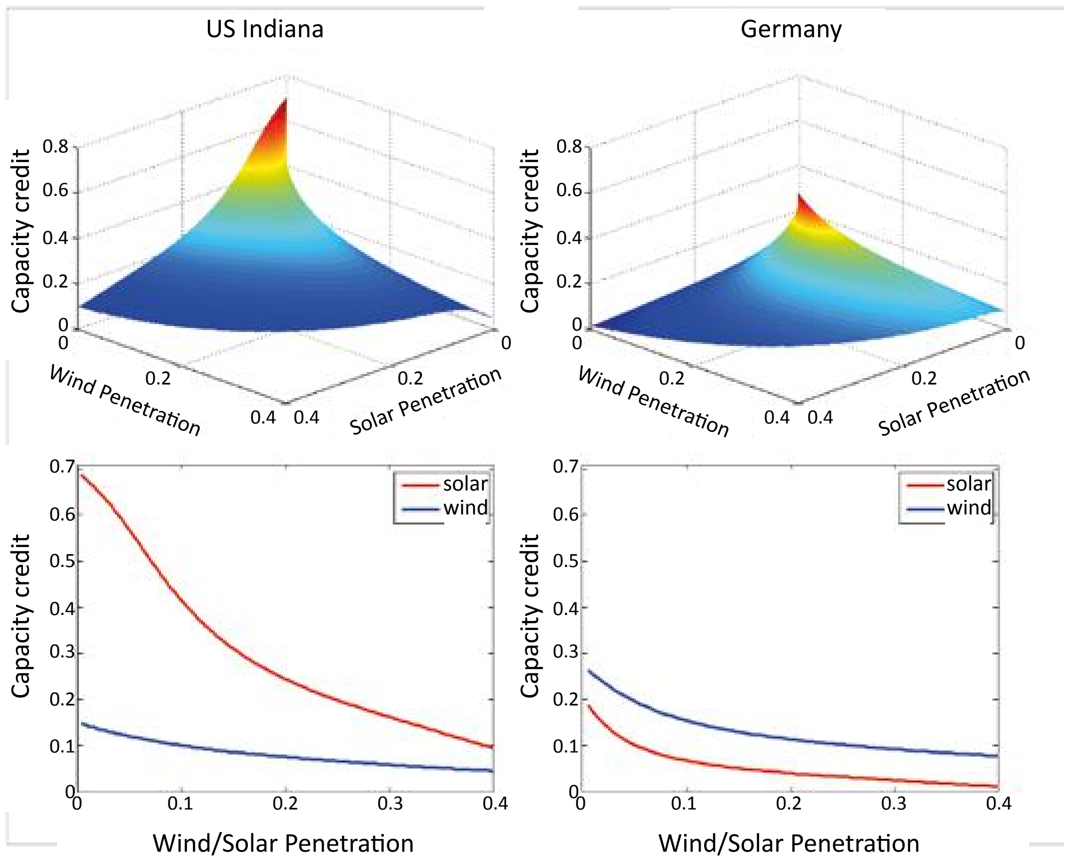


Note on Figure: The Ireland estimates were made for two power system configurations, with 5 GW and 6.5 GW peak load (Holttinen et al., 2009).

Source: Holttinen et al., 2009.

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

Figure 93: The capacity credit for different mixes and penetration of wind and solar PV for Indiana, US (left) and Germany (right)



Source: Ueckerdt et al., 2015.

system, that is, assuming no other measures are taken to increase the system's flexibility. Indeed, a conventional response to the increasing output variability brought about by increasing penetrations of renewables would be to maintain and commission increasing amounts of back-up plant. This could be kept on standby and respond rapidly to fill any power gap caused by drops in renewable output. However, the above analyses of capacity credit suggest significant problems with this approach, as beyond a certain level of installed capacity of renewables, increasing installations enable vanishingly small displacements of conventional capacity. Attempting to balance a system with high quantities of variable renewables, where the only available strategy is maintaining conventional thermal fossil standby plant, would entail vastly increasing the overall capacity of the supply system. This would require large numbers of plant to be kept on standby. Such a system would very likely be expensive, resource inefficient, and would negate some of the low-carbon benefits of the renewables it sought to deploy. UN Environment (2015b) reports that studies from North America and Europe suggest that the requirement for increased system flexibility as a result of increased wind power, if met through keeping thermal plant on standby, would increase GHG emissions in the range of 5–70 gCO_2e per kWh of wind energy generated.

For this reason, other solutions to the temporal balancing problem are critical if significant quantities of renewables are to be deployed. One such solution could be to increase the electricity storage capacity available on the system. Energy storage compatible with electricity systems is potentially available through technologies such as pumped-hydro storage, flywheels, compressed air energy storage, batteries, and electrolysis/fuel cell systems. Of these technologies, currently only pumped-hydro storage has substantial levels of deployment, accounting for 99 percent of electricity grid storage capacity globally (Geth et al., 2015). Energy storage technologies are currently commercially viable for specialized and high-value services, for example "peak shaving" (helping meet the very highest peak demands of the year)(Rehman et al., 2015), or providing ancillary services such as frequency regulation (Du, 2015, Günter and Marinopoulos, 2016). However, they are not yet considered to be cost-effective options for routinely time-shifting large quantities of energy due to the kind of major supply-demand mismatches that might occur in a renewables-dominated system (Kear and Chapman, 2013, Staffell and Rustomji, 2016).

Future cost reductions are of course possible, particularly with strong policy support. One key issue is the round-trip conversion efficiency of many storage technologies, especially over longer periods. While for specialist, high-value services, round-trip efficiencies of 75–80 percent (Gallo et al., 2016) may be acceptable, this kind of efficiency penalty could be problematic if incurred on the kind of scale that could be needed to balance a high-renewables system on a regular basis. In terms of environmental impacts, UN Environment (2015b) finds that "there has been little analysis of the environmental and resource impacts of utility-scale storage", but that indications can be drawn from looking at smaller-scale systems. For example, lithium ion and sodium sulphide batteries are said to have life-cycle emissions of 30–100 gCO_2e per kWh of electricity stored.

A more resource-efficient approach to managing low-carbon electricity systems may be to encourage greater demand-side flexibility, by providing greater incentives for users to be flexible regarding the times that they place demand on the electricity system. For example, if the price of electricity at any given time reflected the marginal cost of providing another unit, it would be more expensive at the times when providing that extra unit required firing up, at short notice, an inefficient and polluting thermal standby plant. This situation could occur either during peak demand, in which all but the most expensive plants were operating at close to full output; or in a future low-carbon system, it could be caused by a drop in renewable output requiring the resort to the standby plant. At such a time, those users who had the choice to delay their consumption of electricity would be incentivized to do so. Conversely, there would be other times when the price of electricity would be very low, when overall demand was low and supply very plentiful, for example due to high renewable output. Users who could move their demand to this time would benefit from very low-cost electricity, as the marginal cost of electricity when there is excess renewable power would be close to zero.

There are of course some users and demands that are inherently inflexible and would not be able to participate in such demand-side response. Further, having to constantly check the price of electricity and compare it with past and predicted future prices could prove highly inconvenient to individuals. However, both institutional and technical innovations are emerging which could manage this. These include specialist energy management companies, or "demand-side aggregators", which act as a coordinating intermediary between energy-using clients and the system or network operator. By making use of existing electricity market opportunities, such operators are creating value from simple demand shifting, with no adverse impact on the customer (Harrabin, 2013, Timperley, 2016). At the household level, there is potential for smart technologies that automatically respond to signals from the grid to identify the best time to switch themselves on (Bilton et al., 2014). The overall economic benefits at the system level of such demand-side response appear to be strong, which reflects the resource benefits of avoiding constructing and operating rarely used and inefficient standby power plants (Bradley et al., 2013). However, these system-level benefits are not always maximized, because power systems are not always designed in such a way that provides participants — including small- and large-scale, supply and demand-side actors — with the incentives and price signals that reward these kinds of demand-shifting activities. Thus, within power systems (as is often also the case more generally), intelligent policy design can encourage actors to act in more resource-efficient ways – and reward them for doing so – to the overall benefit of the system (Bradley et al., 2016, Dong et al., 2016, Shen et al., 2014, Warren, 2014, Zhang et al., 2017).

6.3.3.2. Spatial

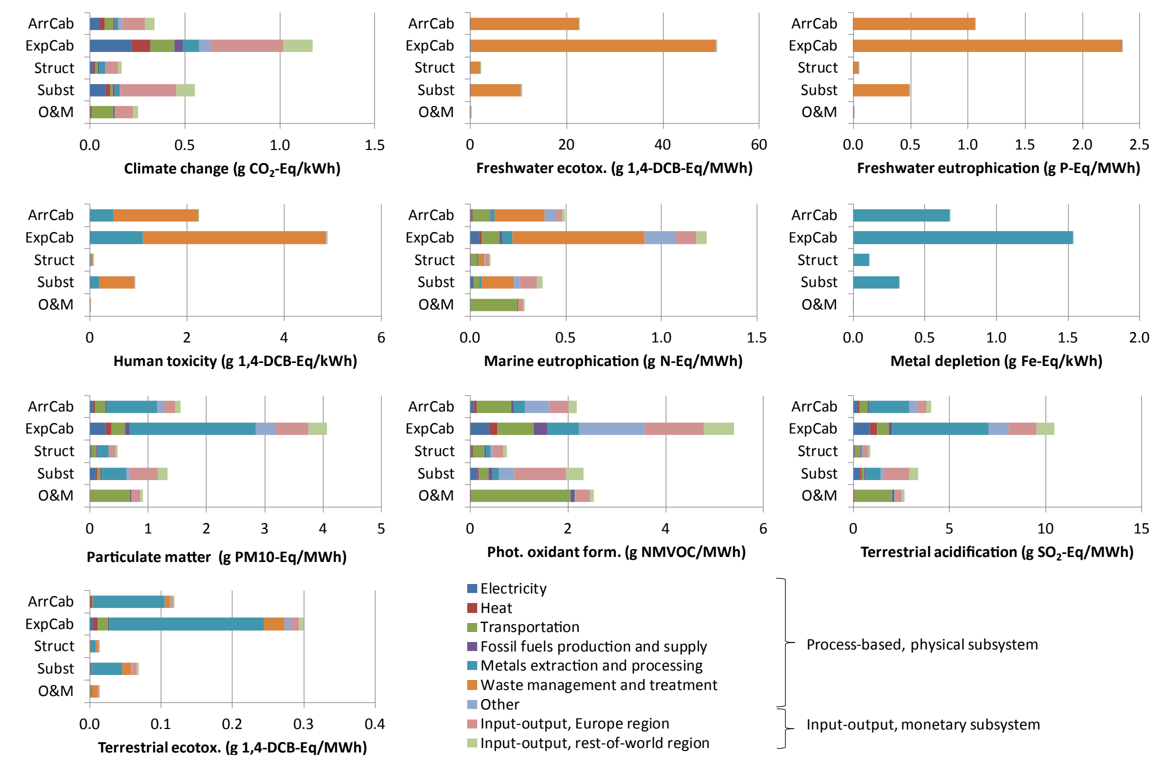
Electricity systems are also networks that operate over a certain space, connecting various supply and demand nodes within a geographical area through electrical transmission and distribution wires. Electricity systems can tend to be large scale — with large, remote power plants connected to demand centres via long-distance high-voltage transmission wires — or smaller scale, with smaller plants more closely co-located or embedded within centres of demand, connected on lower-voltage distribution wires. There are economic, environmental and resource-related advantages and disadvantages to each option.

There are potential advantages to having small-scale generators closely co-located with local demands. Firstly, transmission and distribution networks incur losses due to the resistance in the wires, and these accumulate over distance. Hence locating smaller generation plants more closely to demand reduces the distance over which power must be transported, potentially reducing losses. Further, there are resource impacts associated with building transmission infrastructure, which again increase with distance. However, such impacts need to be traded off against the benefits that transmission networks can bring, for example increasing the connection of renewables to the power system.

Arvesen et al. (2014) have investigated this issue in detail, carrying out life-cycle assessments of possible future offshore power grids that could connect Norway, Denmark, The Netherlands, Belgium, and Great Britain, through meshed offshore power grids crossing the North Sea. They perform LCAs on two scenarios, which are primarily distinguished by the level of ambition on offshore wind-power deployment. One, called GDv05, produces 538 TWh per year in 2030 from offshore wind, while the other, called ITD20, produces 274 TWh from offshore wind. Due to its lower wind output, ITD20 must produce substantially more electricity from coal (305 TWh per year, compared with 221 in GDv05), and nuclear (50 TWh per year, while GDv05 is nuclear free) (Arvesen et al., 2014). Figure 94 depicts the results of the LCA on the GDv05 scenario, showing that the power export cable makes the largest contribution in all categories.

The total GHG emission intensity of the grid in this scenario is 2.49 gCO_2eq per kWh of electricity transmitted (Arvesen et al., 2014). This can be compared with the life-cycle GHG emissions estimates for generation technologies shown in Figure 86. The comparison shows that the life-cycle GHG emissions of renewable technologies would increase appreciably if they required new transmission infrastructure to be constructed to connect them to the power system. For example, given offshore wind LCA GHG values of 9–11 gCO_2e per kWh, including the emissions intensity of an offshore grid as calculated by Arvesen et al., would raise the total emissions intensity of this technology by around 25 percent. However, Arvesen et al.'s estimate of the GHG emissions intensity of the grid would still be a small fraction of the estimated life-cycle GHG emissions of high carbon emitters such as coal power, at around

Figure 94: Impact indicator results by five components and nine stressor sources per kilowatt-hour or megawatt-hour transmitted for GDv05 scenario



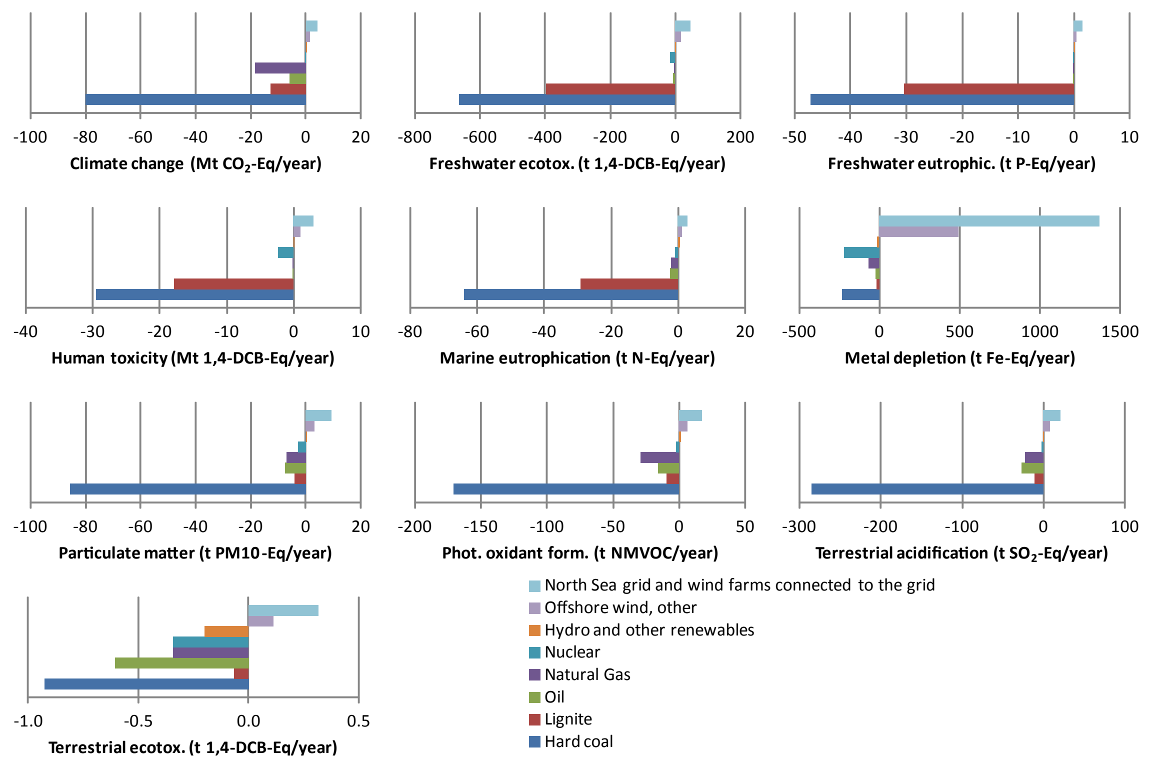
Note on Figure: Ecotox. ecotoxicity, Phot. oxidant form. photochemical oxidant formation. Components: ArrCab array cables, ExpCab export cable, Struct substructure and topside for substation offshore, Subst electrical equipment (voltage source converter, transformer, breakers, and switchgear) for substations offshore and onshore, O&M operations and maintenance (Arvesen et al., 2014).

Source: Arvesen et al., 2014.

800 gCO_2e per kWh, as shown in Figure 86. The practical implication of this is that while the life-cycle GHG emissions of transmission lines are high enough to make it worthwhile, from a GHG reduction perspective, to optimize the arrangement of different low-carbon generators on the system in order to minimize overall requirements for new transmission infrastructure, they are still small enough that in general they would not make a renewable generator more carbon intensive than a fossil fuel power plant. This would be the case even if the former required new transmission infrastructure and the latter did not.

This is indeed demonstrated by Arvesen et al. (2014), when they compare LCA values of the two scenarios (GDv05 with higher offshore wind output, ITD20 with higher coal output) and incorporate the impacts from all generation technologies as well as the North Sea transmission infrastructure. The values in Figure 95 are calculated by subtracting the annual average impact potentials of ITD20 from those of GDvO5. Thus if the bars show positive values it means that the impacts in GDvO5 were greater, while negative values indicate that the impacts in ITD20 were greater. As is clear from Figure 95, for GHG emissions, as well as almost all the other

Figure 95: Net potential environmental burdens (positive axis) or benefits (negative axis) of GDv05 scenario relative to ITD20 scenario



Note on Figure: The length of the bars represents, for eight power transmission or generation technologies individually, the total indicator results for GDv05 less the corresponding results for ITD20, measured on an average annual basis for an assumed lifetime of 30 years. Ecotox. ecotoxicity, Eutropic. eutrophication, Phot. oxidant form. photochemical oxidant formation (Arvesen et al., 2014).

Source: Arvesen et al., 2014.

indicators, the bars are predominantly negative, indicating lower impacts in the high-wind scenario. Thus Arvesen et al.'s analysis suggests that, while constructing new grid infrastructure to support renewables expansion does have environmental impacts, these are in general likely to be more than compensated for by the reduced impacts — across various impact categories — of renewable generation displacing fossil fuel generation.

The one category in which GDv05 impacts are larger than ITD20 is metal depletion, reflecting the higher demand for metals due to the more expanded grid in this scenario. In GDv05, extraction of copper and iron make up 40 and 21 percent of the total metal depletion impact, respectively (Arvesen et al., 2014). The issue of metal depletion, and the extent to which this could be a constraining factor on grid expansion for low-carbon power systems, is an important one. For example, Kleijn and van der Voet (2010) consider the resource implications of a global renewables-only 2050 energy scenario. Their scenario is notably transmission-heavy, not least because it requires 65 percent of world primary energy to be produced by solar PV in deserts, and exported via high voltage direct current (HVDC) power cables. With such reliance on infrastructure, the demand for metals is unsurprisingly high. The authors calculate that the copper required for such a system would be

"about 90% of current reserve base and twice the cumulative production between 1900 and 2001" (Kleijn and van der Voet, 2010). This is of course just one scenario, and it would be possible to imagine alternative low-carbon scenarios with much lower material demand from a less extensive transmission infrastructure. Nonetheless, such exercises are useful to keep in sight potential resource implications of future energy scenarios. Further research is also required to continue developing methodologies for understanding metal stocks, the dynamics of their extraction and use, and for assessing their criticality, as discussed by Gordon et al. (2006), Tilton and Lagos (2007)Jin et al. (2016) Graedel and Reck (2016), among others.

For heat-generating plants, being smaller scale and more closely located to demand would increase their potential to supply waste heat to customers through district heating networks. These could include thermal fossil and biomass plants, and potentially small modular reactor (SMR) nuclear power stations.

Other distributed generation technologies such as PV, if deployed in small arrays within urban areas, might be seen to have an advantage in making use of space within existing urban infrastructures (e.g. unused rooftops), as opposed to taking space in remoter areas where they might be in competition with farming and other land uses.

On the other hand, large-scale systems also have potential advantages. Large-scale power generators are typically able to capture greater economies of scale, which can enable greater efficiencies. Large and remote power stations also offer greater opportunities for end-of-pipe solutions to mitigate pollutants, compared with large numbers of small generators close to demand in residential areas, which can constitute a health risk. A system of large power stations also creates greater economies of scale for CCS infrastructure. This would be a much more complex prospect if it was required to connect to large numbers of small and geographically dispersed power stations.

From a resource perspective, it could also be argued that it makes most sense to locate renewable generators in large capacities in the areas that are richest in that resource. This favours, for example, locating large wind turbines in the windiest areas in northern Europe and the North Sea where wind speeds are highest, and connecting them to demand centres through long transmission lines; rather than attempting to install turbines in low-lying cities because there is demand there, but no wind. Similarly, it could be suggested that solar PV should be installed on a large scale in areas with greatest solar radiation, such as the Southern Mediterranean and Africa, with the potential to export through transmission wires, rather than installing small amounts in more dispersed, but less optimal locations.

The notion of a "supergrid" has been discussed in the European and North African context, and would enable this kind of large export from resource-rich areas. An additional benefit would be the potential to balance out some of the intermittency of the various connected renewables, as due to their geographical distance from each other, there would be a reasonable chance that their times of peak output would not be closely synchronized.

Although transmission losses accumulate for power lines that run over long distances, it should also be recalled that resistive losses decrease as voltage increases. This makes high-voltage lines more efficient carriers of electrical energy than low-voltage distribution lines. As a result, despite the longer distances over which transmission lines travel, in the UK losses from transmission lines amount to around 2 percent of delivered electrical energy, whereas distribution losses are typically closer to 7 percent. Over particularly long distances, high voltage direct current (HVDC) lines are typically used.

In summary, planning and operating electricity systems should involve important questions about increasing the overall efficiency of the operation.

Scale and temporal integration are important aspects of this. The optimal balance will vary between different systems. As systems are transformed by decarbonization, new institutions and ways of operating will be crucial, as will cross-border collaboration.

6.4. Conclusions

This chapter has considered the interactions between resource efficiency, environmental impacts, and decarbonization in the electricity sector.

In order to address the problem of climate change, the energy system as a whole faces a major transformation and scenarios suggest that the electricity sector will need to be at the forefront of this (IEA, 2010c). The significant technological substitution that will need to take place in the electricity sector creates uncertainties, as the technologies have never before been deployed at the kind of scale required by decarbonization targets. It is important therefore for this transition to be supported by careful analysis of the life-cycle impacts of novel technologies, and how they compare to incumbent ones.

A positive conclusion from this chapter is that in most cases, the potential low-carbon technologies identified in scenarios such as IEA's BLUE Map do deliver substantial GHG reductions over their whole life cycle compared with incumbent fossil technologies. Additionally, in most cases they also offer improvements in terms of human health impacts and impacts on ecosystems.

Notwithstanding this broadly positive message, there are of course areas of complexity and uncertainty. These will require ongoing monitoring in order to ensure that low-carbon technology deployment does not create unintentional negative impacts.

While CCS does produce substantial GHG reduction compared with equivalent unabated fossil technologies, its emissions remain higher than renewables and nuclear. However, in terms of human health and ecosystem impact, CCS may actually increase acid pollutants and particulates per unit of delivered electricity, because of the reduced conversion efficiency caused by the capture process. These emissions should be mitigated as much as possible by fitting filters and scrubbers, as with conventional fossil plants. In addition, where toxic emissions emerge from coal mining and processing, clearly CCS is as open to these emissions as conventional practices — and indeed more so per unit of delivered electricity, given its REDUCED efficiency. Measures to improve the environmental performance of extractive industries continue to be an important priority. There is also some uncertainty over the potential impacts if the compounds used in the capture processes are released into the environment. This requires further research.

Biomass chains present considerable complexity, due to the wide range of potential feedstock, transportation and energy conversion combinations. The evidence suggests that these different chains vary considerably in terms of their life-cycle GHG emissions and other impacts. Further LCA work on biomass energy chains is crucial to ensure policy can guard against negative impacts. The potential health impacts of the combustion of different types of bioenergy crop should also be monitored.

The use of material resources tends to be higher for renewables than for fossil fuel technologies per unit of delivered electricity. While there does not seem to be evidence that an absolute depletion of materials could bring a complete halt to the manufacture and deployment of renewables, price volatility could have an impact on the costs of manufacturing renewable infrastructure.

Resource efficiency more generally will be crucial to supporting a low-carbon transition, by reducing demand through efficiency, and on the supply side making cost-effective emissions reductions by delivering energy more efficiently. The efficient management and operation of the electricity system will also be key to a successful transition.

In general, there are a number of positive complementarities between decarbonization and other environmental objectives, as low-carbon electricity technologies tend to reduce other environmental impacts too — with some particular exceptions that need to be monitored. Electricity is also a good example of a sector where resource efficiency complements the low-carbon objective, by making it more affordable and achievable.

7. OTHER AREAS OF GOOD PRACTICE IN RESOURCE EFFICIENCY

Part IIII - Chapters 1 to 6 have explored opportunities for resource efficiency across a range of sectors and materials. This chapter rounds up a number of other areas of resource efficiency potential that were not directly covered within Chapters 1 to 6, but are highlighted by Dobbs et al. (2011) as being among the "15 key areas of opportunity" for resource efficiency.

7.1. Water

7.1.1. Agriculture

As around 70 percent of water extraction is for agriculture, more efficient irrigation techniques offer major potential for water saving. Frequently such techniques also offer the co-benefit of increasing agricultural yields. Compared with traditional flood irrigation, techniques such as sprinklers or drip irrigation can reduce water consumption and increase yields, by applying the irrigation more directly to where it is needed. Drip irrigation involves providing water through a system of perforated pipes that are laid on or beneath the ground. Water drips slowly through the perforations directly to the roots of the crop (Rejwan, 2011). Dobbs et al. (2011) estimate that sprinklers can reduce water use by 15 percent, while increasing yields by 5 to 20 percent, and drip irrigation can reduce water use by 20 to 60 percent, while increasing yields by 15 to 30 percent. However, this is dependent on soils, crop, climate and how the irrigation system is implemented (van der Kooij et al., 2013). Sustaining drip irrigation systems is limited in


Photo: ©Reuters

many areas by salinization associated with soil and water quality issues (Hanson and May, 2011).

In Israel, major constraints on water supply have encouraged a range of water-saving innovations: about 84 percent of the country's domestic wastewater is now reclaimed for irrigation purposes. This helps ensure that about 52 percent of agricultural water demand comes from non-potable sources — domestic wastewater supplemented with brackish (salty) water. Israel has extensively adopted drip irrigation in its agriculture sector, in combination with computerized control systems that provide the exact required amount of water directly to the plant roots. The uptake of water efficiency measures across sectors is stimulated by a range of incentives as well as penalties, targeted at different users. For example, a water quota system for farmers places a strict limit on consumption of potable water, but also rewards under-consumption, and farmers benefit from a lower tariff for using non-potable water for irrigation. For domestic users, differentiated tariffs are available, allowing low users to benefit from a lower charge, with extensive metering providing consumers with the information to monitor their consumption. Incentives and penalties are also directed at the water supply utilities, which are charged for avoidable losses. They are allowed to keep low water pressures as this reduces leak-loss rates. The government also engages in research and development in order to develop new technological innovations in the area of irrigation (Rejwan, 2011).

Significant barriers to the application of advanced irrigation techniques include a lack of information, and a lack of capital to invest in such technologies, especially for smallholders and farmers on marginal land. However, there are other less capital-intensive ways of achieving a similar aim. Tensiometers are devices that can precisely measure the moisture content of the soil to allow more precise irrigation. These have been employed by rice farmers in Punjab, India, who have consequently reported 33 percent water savings (UN Environment, 2014a). "Smart irrigation scheduling" aims to provide the specific amount of required water at the specific time it is required, to avoid over-irrigating (McCready et al., 2009). Modern ICTs have also been used in Uganda to enable farmers to access information on weather forecasts, thereby improving irrigation timings and water management (UNCTAD, 2011).

Although applying exactly the optimal amount of irrigation is of course desirable, in particularly water-scarce areas, "deficit irrigation" can be practised. By applying only 50 percent of the full irrigation requirement, the yield is compromised by only 10 to 15 percent. In rice cultivation, the traditional approach is to maintain a pond of 3–5 cm standing water. However, allowing the ponded water to disappear, and only reapplying irrigation after 3–4 days (known as "alternate wetting and drying") reduces water use by 20 to 30 percent without significant yield reduction (Ali and Ali, 2008).

Where advanced technologies are not available, even relatively simple interventions can improve water efficiency. For example, ActionAid reports that in West Africa, stone barriers built alongside fields can reduce the flow of water run-off during the rainy season. This improves soil moisture,


Photo: ©AFP

reduces soil erosion and replenishes groundwater. This simple technique can improve the land's water retention by five to 10 times, and the biomass yield by as much as 10 to 15 times where run-off can be captured from upslope areas (ActionAid, 2011). Other effective soil-moisture management techniques for rain-fed areas are structures such as furrows, vegetative strips or bench terraces (FAO, 2011c).

7.1.2. Municipal

There are examples of relative and absolute decoupling of water use from GDP, particularly in countries and cities in which water shortage and scarcity are issues of concern. For example, between 2001 and 2009, Australia's GDP grew by 30 percent, while its water consumption reduced by around 40 percent. This was achieved at negligible cost, through cost-effective measures in water efficiency and demand reduction (UN Environment, 2014b).

Reducing water consumption in toilets and bathrooms, and reducing leakages in the pipeline distribution system, are considered the most efficient approaches to water conservation in urban areas(Sharma and Vairavamoorthy, 2009). Specific technologies include low-consumption toilets, low-flow showers and water-saving sinks (Sharma and Vairavamoorthy, 2009). Fittings on appliances that reduce their water flow have been implemented in Australian cities such as Melbourne (UN Environment, 2013a), and in New South Wales new building developments and renovations must submit a certificate showing 40 percent reduction in potable water use (Burgin and Webb, 2011).

Reducing leaks from water supply is also a priority in many areas. Water losses due to leaks and unaccounted flows range widely, with estimates ranging from 5 percent to 80 percent of supply. The variation depends on the level of infrastructure development, as well as management and operational practices (UN Environment, 2015e). Dobbs et al. (2011) estimate that there is significant potential to reduce water leakage from municipal sources, calculating that 100–120 billion cubic metres of water could be saved by 2030 as a result of reducing leakages in the supply to commercial, residential and public buildings. Furthermore, persistent high water losses have been linked to lack of revenue collection for water: the World Bank estimates that 40 percent of water produced in Indian cities is either lost in leaks or not billed to the customer (Agrawal, 2008), while UN Environment estimates that non-revenue water proportions can be as high as 70 percent in some countries (UN Environment, 2014b). Also due to lack of revenue collection, water utilities may have little incentive or available capital to make timely investments in infrastructure (Dobbs et al., 2011).

Water is subsidized in many countries, with Kochhar et al. (2015) estimating that in 2012 global water subsidies totalled US$456 billion, leaving little incentive to conserve water. If the utility is unable to capture sufficient revenue to reinvest in the infrastructure, the system can become even more inefficient in the long run, with its financial sustainability undermined. Kochhar et al. (2015) note that whereas "getting incentives right, notably by reforming water pricing, can help rationalize water use, promote needed investment, and protect the poor", subsidies may in contrast be inequitable, as they disproportionally benefit upper-income groups, who have better access to, and use more water. If the purpose of the subsidy is to protect the access of the poor to water, this can be achieved in other ways that are more cost-effective, provide funds for reinvestment and maintain incentives for conservation.

In the Paraiba do Sul river watershed in South-East Brazil, gradual increases in the price of water began in 2003. The higher prices increased the water utility's income, which it was then able to invest in water management. The higher prices also prompted more water conservation: extraction was reduced by 16 percent and consumption by 29 percent between 2006 and

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

2008. Companies were motivated to invest in water-saving and reuse technologies (UN Environment, 2014a).

An important principle for further improving the efficiency of water use is that of cascading uses of water. This principle suggests that not all uses of water will require a water quality as high as that required for drinking water. For example, harvested rainwater can be used for various purposes, as is now common in Australia (Burgin and Webb, 2011). Grey water — water that has been used for washing — can be reused without treatment for other uses, such as watering plants or flushing toilets. More than half of all households in Australia reuse grey water in some form (Maheshwari, 2006). It was reported in 2001 that in California in the mid-1990s, grey water was used for "irrigating landscapes, golf courses and crops, recharging groundwater aquifers, supplying industrial processes and even flushing toilets" (Gleick, 2001).

In Accra, Ghana, a kind of cascading water use had emerged, albeit an unsafe one: domestic wastewater was flowing untreated through streams that were the primary source of irrigation for small-scale urban farmers. A project intervened to set up a low-cost natural treatment system to make the wastewater safe for irrigative uses (Reymond et al., 2009). Provided that contaminants can be removed to avoid health risks, wastewater can be highly suited to irrigation, as it has the advantage of being rich in nutrients (FAO, 2011c).

Given the trends of population increase and urbanization, efficient use and application of water, and its reuse through recycling or cascading systems, as discussed above, are crucial strategies. However, water-use efficiency has to be viewed in the context of the complete hydrological cycle. In those parts of the world where excessive withdrawals of groundwater are posing unsustainable demand (FAO, 2011c, WWAP, 2015), sub-basin level recharge strategies, including watershed management, have to be made part of water-use efficiency.

7.1.3. Industrial and commercial

Industrial and commercial sectors can also be significant water users, but there are numerous examples of good practice. For instance, the steel industry consumed water at a rate of 200–300 tonnes per tonne of steel in the 1930s and 1940s, which has now radically reduced to typically 3–4 tonnes per tonne of steel (Gleick, 2002). BlueScope Steel's Port Kembla Steelworks, Australia, has reduced freshwater consumption to 0.9 tonnes per tonne of steel, and aims to eventually use entirely recycled water or seawater. In the aluminium sector, Alcoa's European Mill Products business has achieved a 95 percent reduction in water consumption through a closed-loop system. Meanwhile, the BP Kwinana Oil Refinery south of Perth, Australia, has reduced freshwater use by 70 percent and wastewater by 40 percent. Visy Industries Australia Tumut Paper and Pulp Mill has achieved an 80 percent reduction in average water consumption, while Amcor Australia has reduced freshwater use by 90 percent at their Cartonboard Mill in Petrie. Intel's Arizona facility uses 75 percent less water than the IT industry average, and Pilkington Glass Australia reduced water consumption per piece by 61 percent in five years. Through water recycling, Ingham's Enterprise has reduced water usage by 72 percent at their Brisbane poultry processing plant. Lastly, best-practice breweries in Australia now achieve one third of the water consumption per litre of beer of the industry standard (Smith, 2011d, Smith, 2011c, Smith, 2011b, Smith, 2011a).

Industrial and commercial water-use efficiency and reductions in wastewater generation can also be achieved as a result of industrial symbiosis arrangements. The industrial symbiosis concept was introduced in Part III - Section 6.4.3, with examples of "eco-towns" and other industrial symbiosis arrangements in Japan, China, Korea and the UK. Such eco-towns, or eco-industrial parks, can improve the management of water and effluent waste by optimizing collection and treatment from a number of users, and finding ways to coordinate the water cycle through the

various water-using processes and activities in the town or park (WWAP, 2015).

One example is the China-Singapore Suzhou Industrial Park in China. The result of a joint government collaboration between China and Singapore, it brings together more than 90 Fortune 500 companies, but also has around 600,000 residents. Its main industries are electronics, telecommunications and precision machines (Yu et al., 2015a, WWAP, 2015). The park has instituted various measures and charges that encourage its businesses to be more resource efficient. One of these is a water quota pricing system, under which a company exceeding its quota pays a 50 percent higher rate for its water use. In addition, the geographical proximity of the industries and the centralization of services and infrastructure also create opportunities for water savings. A central utility has been created for the operation of the park's water, energy, waste and other services, enabling centralized wastewater plants and infrastructure to treat industrial and domestic sewage. Reclaimed water is used for cooling at a cogeneration plant, for which wastewater sludge is dried and used as a fuel. During drying, condensate is collected and sent back to the cogeneration plant, saving water and heating costs of 1 million RMB/year (Yu et al., 2015a).

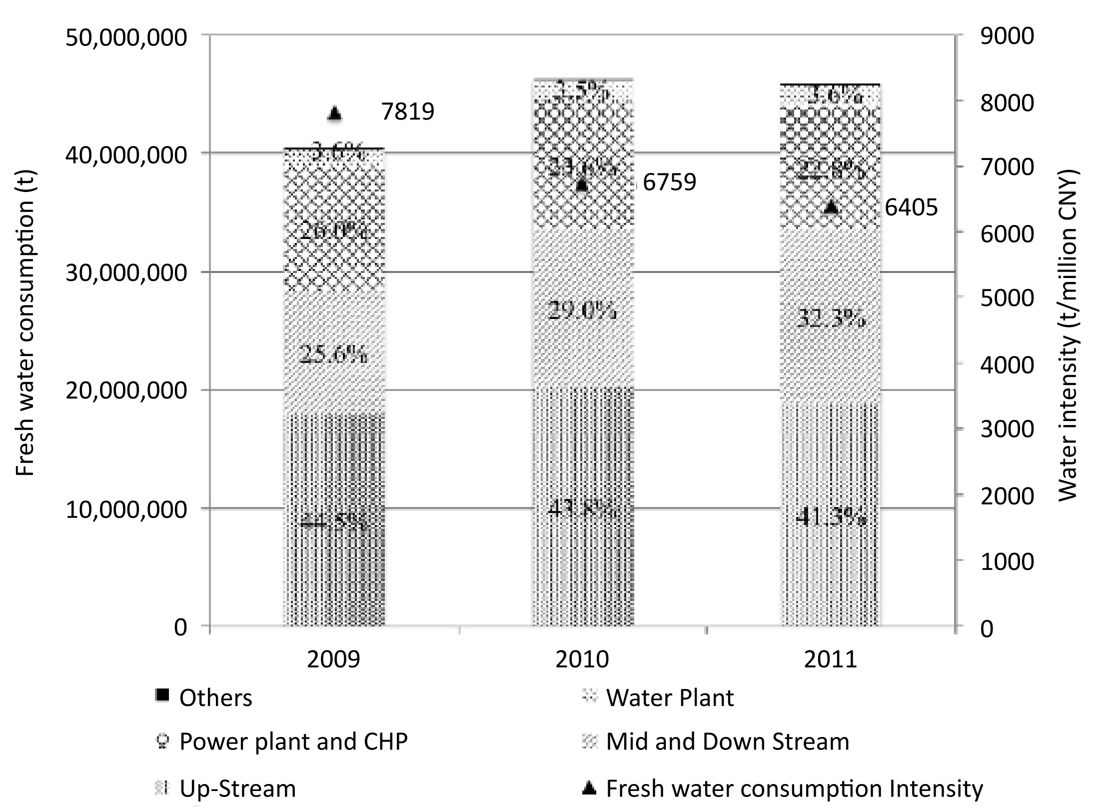
Yuan et al. (2010) also report that sharing the infrastructure around the wastewater treatment plant has benefits for the companies within the park. Further, Gold Huasheng Paper Company has built a water-reclaiming system internally, with funding from the park. The system enables it to reduce its wastewater discharge by 2.6 million tonnes per year, and save 25 million RMB per year from avoided water rates and pollution fees. In the park as a whole, wastewater increased between 2006 and 2012 as a result of increased industrial activities. However, the rate of increase was less than the increase in economic output, meaning that in most years relative decoupling of wastewater emission intensity was achieved (Yu et al., 2015a).

The Shanghai Chemical Industry Park in China is a grouping of chlorine chemistry industries (WWAP, 2015). It has about 40 firms, around 80 percent of which are foreign owned, and half Fortune 500. The economies of scale created by integrating water supply, wastewater treatment and solid waste management around a centralized infrastructure generate savings for consumers. Organic and inorganic wastewater, rainwater and municipal wastewater are collected separately for more effective treatment, while an experimental artificial wetland is in development to further treat effluent before final discharge. Reuse of water between industries is also a priority: there is an ongoing project to capture the high salinity wastewater from the Bayer polycarbonate plant for use at a chloro-alkaline plant, with the plants connected via a 6 km pipeline. Elsewhere, seawater is being used instead of freshwater for industrial cooling (Yune et al., 2016). As shown in Figure 96, although freshwater consumption did not reduce between 2009 and 2011, the intensity of freshwater use per unit of economic output did decrease, suggestive of efficiency improvements and at least relative decoupling (Yune et al., 2016).

Tian et al. (2014) assess the performance of 17 eco-industrial parks in China, over periods ranging from two to four years. They find that total freshwater consumption across all 17 parks for the periods studied grew by 18 percent. However, all parks showed relative decoupling of freshwater consumption from economic output (measured as industrial added value). The reduction in freshwater consumption intensity ranged from 3 to 65 percent across the different parks, and the average reduction across all parks was 25 percent (Tian et al., 2014).

Tewari et al. (2009) discuss water-use efficiency in Indian pulp and paper industries, which can be highly water intensive. However, measures are available to reduce water consumption and wastewater production. These include improving pulp washing to require freshwater in only one stage, and various opportunities to recirculate water during the process. The authors report that such measures have achieved cost

Figure 96: Freshwater consumption and water intensity in Shanghai Chemical Industry Park



Source: Yune et al., 2016.

savings. However, for some small- and medium-scale units, the initial investment costs of such measures may be prohibitive. The authors suggest that this barrier could be overcome through common recovery or treatment systems shared by mills located in clusters, which would allow mill owners to share and spread the upfront costs of such investments.

Saha et al. (2005) and Tewari et al. (2007) investigate the prospects for reducing water use in Indian distilleries. Measures can include: appropriate reuse of washwater; counter-current operation in bottle washing; recycling of cooling water; optimization of cooling tower design; modifications to the fermentation process such as continuous (as opposed to batch) fermentation; and minimizing dilution in processes such as effluent biomethanation (Saha et al., 2005, Tewari et al., 2007).

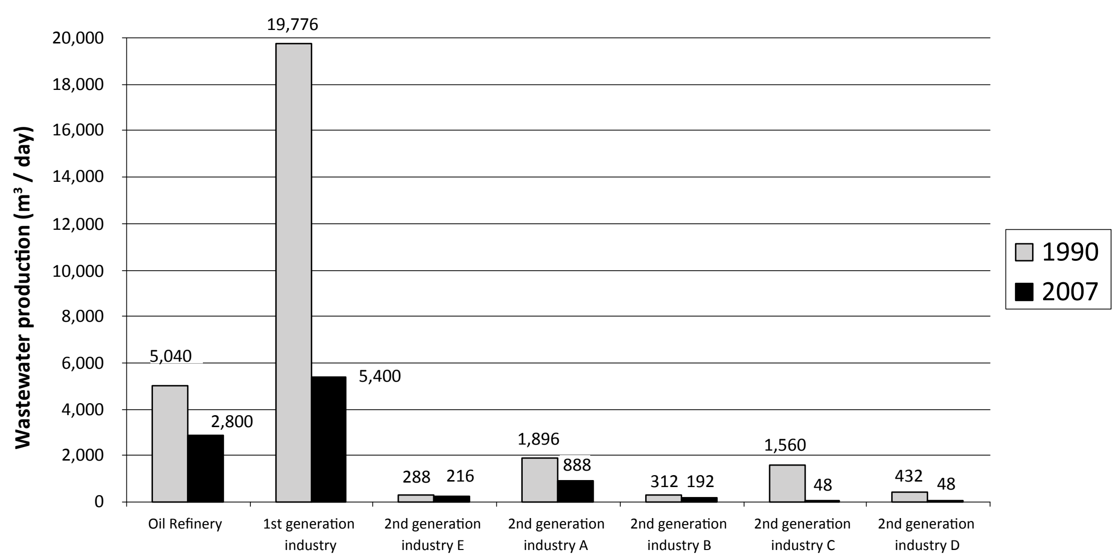
Ribeiro and Kruglianskas discuss the impact of performance-based regulation and an environmental permitting scheme on water consumption in industries in Sao Paolo state, Brazil (Ribeiro and Kruglianskas, 2013), which was first established in 1976. From 2002, a number of important changes were made to the regime, notably including procedures for periodic renewal of the permits, on the condition of continuous improvements in performance. Industries also now had the opportunity to extend their permits by 30 percent of their original time period if they received a successful environmental performance evaluation, providing a further incentive to continually improve performance.

An important instrument within the process is the Environmental Improvement Plan (PMA), which does not have rigidly predetermined content. Its purpose is rather as "an instrument for negotiation and dialogue between businesses and the Environmental Agency with regard to propositions to improve environmental aspects during permit renewal". Ribeiro and Kruglianskas (2013) focus on the case study of the Capuava Petrochemical Hub, a major industrial complex that is responsible for 27 percent of Sao Paolo state's collected VAT, and which is situated in an environmentally fragile region, amid large water bodies and tropical forest. In 2005, most of the companies in the hub were invited to engage in the permit renewal process. The companies' PMAs included various measures relating to water use, including improving water-use efficiency, reducing water losses, closing water-cooling loops, and improving water reuse through technologies such as reverse osmosis membranes (Ribeiro and Kruglianskas, 2013). Figure 97 compares wastewater generation for a selection of the most important companies in the hub in 1990 and 2007. It shows substantial reductions over this period, during which the output production of the hub itself more than doubled (Ribeiro and Kruglianskas, 2013). This suggests that the performance-based environmental permitting regime had a positive effect on the companies in the hub, encouraging them to increase water-use efficiency and decrease pollution intensity.

7.2. Land degradation and restoration

As noted in Part I, continuation of current trends in land degradation could result in a considerable loss of productive land and need for further cropland expansion. Hence, the restoration of degraded agricultural land, and the protection of currently stable or mildly degraded land through practices that retain soil nutrients, soil organic matter and soil mass, are important strategies towards improving the overall productivity of agriculture while reducing resource and environmental impacts.

Figure 97: Comparison of total wastewater generation of main industries in Capuava Petrochemical Hub, Sao Paolo state (m^3/day)



Source: Ribeiro and Kruglianskas, 2013.

An important strategy for preventing land degradation would be to encourage farmers to adopt low-till or no-till farming practices. Tilling is the preparation of soil for planting, which significantly improves crop establishment, yet its undesirable consequences include soil compaction, loss of organic matter, erosion and disruption of soil microbes. Low-till or no-till practices aim to prepare the seed bed with minimal soil disruption (Anon, 2016). The provision of certification programmes, extension services and training will be important drivers for widening the adoption of such practices (Dobbs et al., 2011).

As for high-input agricultural systems, they tend to entail greater environmental impacts, and may in any case be unaffordable for low-income farmers. Monteith (1990) describes a sustainable land management system as one in which "outputs do not decrease when inputs are not increased". A number of integrated approaches aim towards this ideal, such as agroecological approaches, conservation agriculture, organic agriculture, agroforestry and integrated crop-livestock systems (FAO, 2011c). As one example, Altieri (2002) identifies a number of principles of sustainable agroecology:

- Recycle and reuse all available biomass within the farming system
- Grow plants by building soils, soil organic material and biotic activity
- Minimize soil losses by protecting land from direct solar radiation, strong winds and erosive water flows
- Maximize diversity to increase resilience
- Enhance biological interactions and synergies

The specifics of implementing these principles vary in different contexts. Plant diversity has been shown to improve soil health, nutrient cycling and biodiversity: for example, planting legumes among other crops offers nitrogen fixation. Similarly, planting leguminous trees alongside crops can improve soil fertility through nitrogen fixation, by creating more soil organic matter, and due to the fertilizing effect of dung from animals that graze in the shade of the tree. In Zambia, 160,000 farmers have planted the nitrogen-fixing African acacia *Faidherbia albida* among their crops, which sheds its leaves during early rainy season and remains dormant during the crop-growing period. This means it does not compete for light, nutrients or water during the crop-growing season. According to Zambia's Conservation Farming Unit, maize yields from fields planted with acacias averaged 4.1t/ha, compared with 1.3 t/ha outside the tree canopy (FAO, 2011c).

As mentioned above, zero- or no-till practices can help protect soils and reduce moisture loss. The benefits of reusing all available biomass may pay particular dividends in integrated crop-livestock systems. In such systems, manure from livestock may be transferred to the soil to improve its fertility, and crop residues may provide additional feed for animals (FAO, 2011c).

Restoring degraded land can be capital-intensive, which can constitute a barrier in regions where land ownership is not clear, and where farmers occupying the land do not have the capital to make the required investments. However, many of the principles described above do not necessarily require major capital investment. Nonetheless, they do require knowledge, in order to maximize synergies by implementing the right combination of measures in each specific context. Thus, another important barrier is lack of information and education. As UN Environment (2014a) notes, "there is a large need to expand the outreach and extension education efforts to ensure that research results on improved management practices are transferred and adopted rapidly by farmers". Numerous efforts to improve farming practices therefore focus on improving knowledge-sharing and communication between farmers. For example, projects in Tanzania and Malawi showed the importance of networking between farmers for disseminating knowledge (Majule et al., 2011). Further, "plant clinics" have

Photo: ©Reuters

been set up in 14 countries, as local meeting places where farmers can seek advice from local experts. Boa and Bentley (2009) estimate income increases averaging US$801 per hectare for farmers receiving advice from such clinics. Meanwhile, in Central America, the Campesino a Campesino (Farmer to Farmer) network is another example of knowledge-sharing (UN Environment, 2014a). These principles also apply in temperate agricultural systems worldwide.

Often the most cost-effective strategy for sustainably increasing production is simply better matching land use with land potential through effective land-use planning (UN Environment, 2014a). This both limits the need for restoration by minimizing degradation, and focuses intensification and climate change adaptation investments where they are likely to yield the highest financial returns (Herrick et al., 2016).

There are numerous environmental benefits associated with less intensive farming methods. In a comparison of conventional and organic farming systems, Hülsbergen and Küstermann (2007) found the GHG emissions to be three times higher in the conventional case. However, in developed countries the market pressures and tight margins experienced by farmers mean that high-input systems are incentivized. This context poses a challenge to organic farming, as its yields can be significantly lower, depending on soil type and other conditions (Seufert et al., 2012). However, Ponisio et al. (2014) find that diversification techniques such as multi-cropping and crop rotation can substantially reduce the yield gap between organic and conventional systems.

In the EU context, Buckwell et al. (2014) call for "added knowledge which will affect how physical inputs are combined and managed",

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

or in shorthand "more knowledge per hectare". Buckwell et al. (2014) report on a study by Elliot et al. (2013) comparing 20 UK farms on five indicators: food production intensity, carbon footprint, nitrate losses to water, ammonia losses to air and biodiversity. One of the farms (a mixed farm) was performing well on all indicators, and three others were performing well on at least three criteria and moderately on the others. The study shows, first of all, that measuring performance is possible and may be a useful guide to improving performance. Secondly, it indicates that good performance across a range of environmental criteria is possible at the same time as achieving high food productivity. Buckwell et al. (2014) describe this outcome as "sustainable intensification".

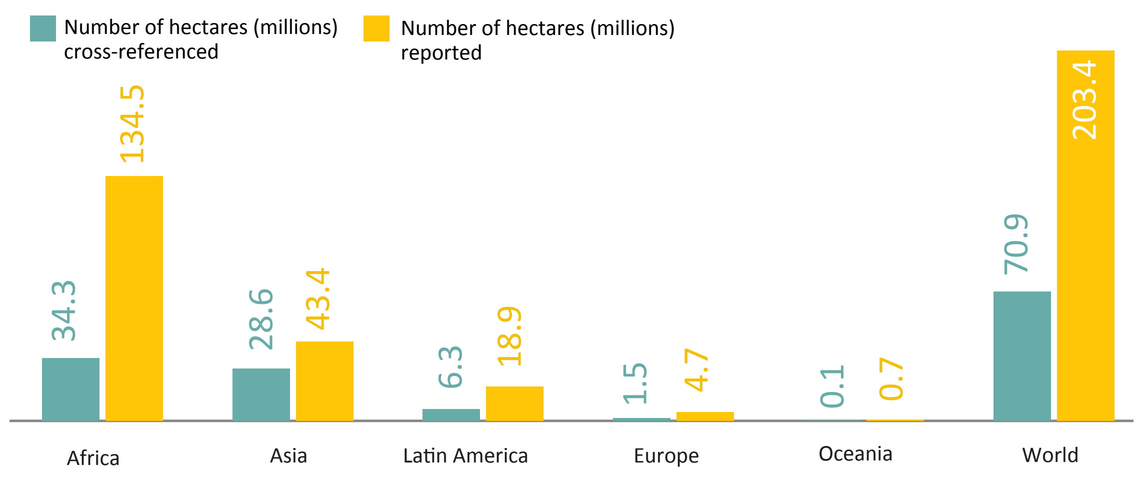
Nutrient loss from soils can be mitigated by recapturing nutrients from food-chain waste, as well as other waste streams, and reapplying them to soils. Senthilkumar et al. (2014) report that, in the case of France, the recycling efficiency of phosphorus is 51 percent across all waste streams: 75 percent for industrial waste, 43 percent for household wastewater and 47 percent for municipal waste. BMUB (2015) reports that the German Government is examining potential measures to increase rates of phosphorus recovery from waste streams such as sewage sludge, wastewater, slurry and fermentation residues. Significant dissipation of phosphorus also occurs in industrial processes. In Japan, the quantity of phosphorus contained in dephosphorization slag from steel-making is comparable to its total imports of phosphate ore. The technologies being proposed to recover phosphorus from this source could create a significant new phosphorus stream (UN Environment, 2013c).

Governments have been significant players in initiatives to reduce degradation within their own national boundaries. For example, China has instituted a soil erosion control programme in eight of its regions (UN Environment, 1997). In Paraguay, the Ministry of Livestock and Agriculture has instituted a Sustainable Natural Resources Management project, which aims to improve farming techniques by transferring financial incentives through local Farmers' Committees. The project has resulted in significantly increased yields for farmers (UN Environment-MercoNet, 2011). In Finland, the Government has linked the allocation of subsidies to sustainable fertilizer use. To receive the subsidy, farmers must follow set criteria relating to the maximum fertilizer rate for each plant and soil type (UN Environment, 2014a). A similar principle operates at the EU level, where EU subsidies are partly tied to compliance with environmental performance, and uptake of agri-environment measures (UN Environment, 2014a). In Malawi, a government Agroforestry Food Security Programme promoted the uptake of nitrogen-fixing trees, in order to move farmers away from subsidized fertilizer. The programme now involves 200,000 families.

Dobbs et al. (2011) suggest that private sector agribusinesses may also become interested in rehabilitating land in order to grow high-value crops. However, UN Environment (2014a) raises potential concerns about the significant growth in large-scale land acquisitions by private companies and by national governments purchasing land in other countries. Foreign direct investment in agriculture rose from around US$600 million annually in the 1990s to an average of US$3 billion between 2005 and 2007. This land rush is thought to have been driven by a perceived risk of food shortages, economic recession and biofuel targets, as well as investor speculation. Figure 98 shows that the land rush has been particularly significant in Africa.

It can be argued that large-scale land investments can bring benefits by generating revenues and increasing agricultural productivity, building up export agriculture which can support national economic development. However, case studies to date have revealed more negative than positive

Figure 98: Regional focus of land acquisitions, 2000–November 2011 (Mha)



Source: Anseeuw et al. (2012) based on the Land Matrix (www.landmatrix.org). "Reported" (red columns) indicate that the land acquisition was reported by at least one source (published research and media reports). "Cross-referenced" (blue columns) indicates that more than one source of information reported the same land acquisition. Numbers have been rounded.

impacts, including human rights abuses, environmental impacts and corruption. Clashes occur when areas of land being used under traditional or customary law are sold by governments as unoccupied. Furthermore, large-scale high-tech agriculture can be geared towards export, doing little to reduce hunger in local populations. Private investment in agriculture can result in investors with no involvement in the land and with interests more around short-term returns than long-term sustainability. In light of these concerns, the Hunger Task Force of the United Nations Millennium Project and IAASTD support peasant agriculture as a fundamental effort in the struggle against poverty and hunger (UN Environment, 2014a). The 38th Session of the Committee on World Food Security, 2012, produced "voluntary guidelines" on land tenure. These acknowledged the importance of secure and equitable access to land, as the "eradication of hunger and poverty, and the sustainable use of the environment, depend in large measure on how people, communities and others gain access to land, fisheries and forests" (FAO, 2012b).

7.3. Iron and steel energy efficiency

There are considerable untapped opportunities for increased resource efficiency in many major energy-using industries, but they differ by country, by industry, and by process within the same industry. According to IEA (IEA, 2012a), implementing the best available technologies could reduce industry energy consumption by 20 percent from today's level. Examples of increased efficiency potential are given here for just one important sector, steel-making, with figures derived by the McKinsey Global Institute (Dobbs et al., 2011).

The steel industry accounts for around 6 percent of global final energy consumption.

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

The efficiency of steel production has consistently improved, but at a declining rate. Between 1960 and 1980, annual efficiency improvements were in the range of 2 to 4 percent, but between 1980 and 2005 the rate fell to between 0.5 and 1 percent. McKinsey's base case assumption is that efficiency will improve at the rate of 0.7 percent per year between 2010 and 2030, mainly driven by a shift from blast furnaces and basic oxygen furnaces (BOF) to electric arc furnaces (EAF) (Dobbs et al., 2011).

Opportunities for increased efficiency include cogeneration: the recapture of waste heat, to be reused at various stages in the process. This can save 5 to 10 kWh of direct energy, and 95 kWh of electricity for each tonne of steel produced. Coke dry quenching uses sprinklers to recover heat that would otherwise be vented, and can replace around 75 kWh of electricity per tonne of steel.

Other measures within different phases of the process include sinter plant heat recovery, the use of waste fuel, and coal moisture control; these can reduce direct energy use by 50 percent. In BOF steel-making, rolling ("e.g. hot charging, recuperative burners, and controlled oxygen levels" (Dobbs et al., 2011)) can reduce direct energy use by 88 percent and electricity by 5 percent; and pulverized coal injection, top pressure recovery turbines and blast furnace control systems can reduce direct energy by 10 percent and electricity by 35 percent. In EAF steel-making, improved process control, oxy-fuel burners and scrap preheating can reduce electricity consumption by 76 percent. Another opportunity is to shift from blast furnaces and BOF to EAF-DRI (direct reduced iron). However, this process requires a natural gas supply, and thus struggles to be economic where gas is expensive, or coal cheap (Dobbs et al., 2011).

Barriers to implementing these technologies and techniques include, in some regions, information failures and a lack of access to appropriate engineering resources. They also require capital investment, which can be deterred by volatility in both energy and steel prices, and uncertainty about the future of specific plants (Dobbs et al., 2011).

7.4. Oil and coal recovery

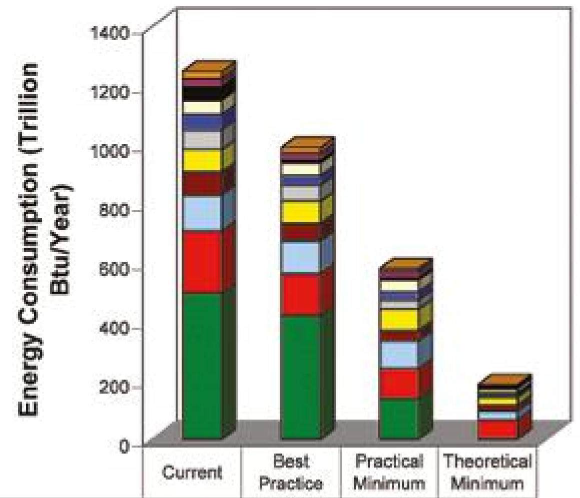
Oil and coal fields often leave a significant proportion of the fossil fuel in the ground, as the resource becomes too expensive to mine further. Various technologies can improve the recovery rates of such operations.

In small-scale coal operations that often work with primarily manual labour, Dobbs et al. estimate that mechanization could improve recovery rates by 50 percent. In China, a barrier to this is the low cost of labour, which means that a mechanized mine is in fact more expensive to operate. However, raised safety standards are nonetheless pushing Chinese mining in the direction of mechanization, as larger mechanized mines have better safety records, as well as higher recovery rates, than smaller non-mechanized mines (Dobbs et al., 2011).

Another optimistic account of the potential for energy saving in heavy industry is given by BCS (2007) in relation to the US mining industry. As shown in Figure 99, the widespread adoption of best practices would reduce energy demand from the industry by 258 trillion Btu per year, a reduction of around 20 percent. Targeted investment in research and development to develop improved technologies would deliver a further saving of 409 Btu per year, providing a total reduction of over 50 percent from current energy consumption levels.

New technologies and best-practice techniques in the oil and coal industries face similar barriers to those in the iron and steel industries. These include, in some regions, information failures

Figure 99: Energy consumption and saving potential by equipment type in US mining industry



	Current	Best Practice	Practical Minimum	Theoretical Minimum
Blasting	24	18	10	5
Dewatering	28	25	23	7
Separations	46	8	7	2
Electric Equipment	48	43	40	13
Crushing	52	32	27	8
Drilling	67	54	32	9
Ancillary Operations	75	75	72	24
Digging	79	60	35	22
Ventilation	122	111	94	29
Materials Handling-Diesel	211	141	101	63
Grinding	494	420	138	2

Source: BCS, 2007, p. 23, Exhibit 18.

and a lack of access to appropriate engineering resources. Likewise, they require capital investment, which can be deterred by volatility in both energy and material prices, which creates uncertainty about the future of specific operations.

In the case of oil fields, enhanced oil recovery (EOR) covers a range of techniques intended to improve recovery rates. Norway's pursuit of EOR is reflected in its average recovery rates of 46 percent, compared with rates in some Middle Eastern countries that have been estimated at less than 25 percent (Dobbs et al., 2011). EOR involves the injection of gas, heat, water or chemicals into the reservoir, thereby forcing more of the oil out and improving recovery rates. CO_2 has the potential to be used in EOR, which could also create some GHG reduction benefits, if the CO_2 had been captured from a fossil fuel that would otherwise have released it into the atmosphere.

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

PART IV: RESOURCE USE AND RESOURCE EFFICIENCY IN THE FUTURE

The next part of the report considers how trends in resource use could extend into the future, and the potential impacts of the widespread implementation of the kinds of resource efficiency measures discussed in previous chapters. Chapter 1 reviews some global and national-level projections and targets, before examining the trends outlined in the UN Environment GEO-5 scenarios (UN Environment, 2012b). Chapter 2 then presents results of modelling commissioned for this report, to explore the economic implications of resource efficiency policies.

1. PROJECTIONS AND TARGETS FOR RESOURCES AND THE ENVIRONMENT

1.1. Global aspirations on resources and the environment

1.1.1. The Stockholm Conference to Rio+20

Governments around the world have been concerned about the impact of human societies and activities on resources and the natural environment since at least the United Nations Conference on the Human Environment (Stockholm Conference) in 1972. Since then, a range of international agreements, plans and declarations have sought to limit these impacts and, in some cases, to ensure that they are kept within the bounds of what the natural environment is perceived to be able to sustain. Table 11 lists an illustrative selection of the main global initiatives of this kind, the goals of which were important precursors of the SDGs agreed in 2015.

Table 11: Main global agreements on natural resources and the environment, 1972–2012

Themes and agreements	Goals
Atmosphere	
United Nations Framework Convention on Climate Change (UNFCCC 1992) Article 2 Cancun Agreements (UNFCCC 2010) Article 1 Paragraph 4 Paris Agreement (UNFCCC, 2015)	Prevent dangerous anthropogenic interference with the climate system
Convention on Long-range Transboundary Air Pollution (CLRTAP 1979) Article 2 World Health Organization guidelines (WHO 2006)	Reduce and prevent air pollution
Johannesburg Plan of Implementation (JPOI) (WSSD 2002) Paragraph 9a Energy for a Sustainable Future (AGECC 2010)	Improve access to reliable, affordable, economically viable and environmentally sound energy supplies

Land	
FAO World Food Summit Plan of Action (FAO 1996) Paragraph 33g Agenda 21 (UNCED 1992b) Chapter 11.12a	Conservation and sustainable use of land Sustain forest cover
UN Millennium Declaration (UN 2000) MDG 1 Target 1c	Eradicate hunger (obviously relevant to land use)
Water	
Johannesburg Plan of Implementation (JPOI) (WSSD 2002) Paragraph 25d UN Millennium Declaration (UN 2000) Paragraph 23	Sustain water resources, protect water quality and aquatic ecosystems
UN Millennium Declaration (UN 2000) MDG 7 Target 7c	Universal provisioning of safe drinking water and improved sanitation
Biodiversity	
Convention on Biological Diversity (CBD) Aichi Biodiversity Targets (CBD 2010) Target 5 CBD Aichi Biodiversity Targets (CBD 2010a) Target 12	Improve the status of biodiversity by safeguarding ecosystems, species and genetic diversity and promote its sustainable use and fair and equitable benefit-sharing
United Nations Convention on the Law of the Sea (UNCLOS 1982) Article 192 Convention on Biological Diversity Decision II/10 (Jakarta Mandate 1995) FAO Code of Conduct for Responsible Fisheries (FAO 1995) Paragraph 6.2	Protect and preserve the marine environment
Chemicals and waste	
Johannesburg Plan of Implementation (JPOI) (WSSD 2002) Paragraph 23 Stockholm Convention on Persistent Organic Pollutants (2009) Rotterdam Convention on the Prior Informed Consent Procedure for Certain Hazardous Chemicals and Pesticides in International Trade (Rotterdam Convention 1998) Article 1	Reduce chemical pollution to protect human health and the environment Monitor and control the trade in certain hazardous chemicals
Johannesburg Plan of Implementation (JPOI) (WSSD 2002) Paragraph 22	Minimize the amount of waste and promote reuse and recycling

Source: UNEP (2012b), Table 16.1, p. 426.

1.1.2. The Sustainable Development Goals (SDGs)

As noted above, the SDGs were agreed by the United Nations General Assembly in 2015. Table 12 lists the SDGs that have important components related to natural resources and the environment.

Table 12: SDGs and associated targets related to natural resources and the environment

Sustainable Development Goal (SDG)	Associated targets
SDG 1: End poverty in all its forms everywhere	1.5: By 2030, build the resilience of the poor and those in vulnerable situations and reduce their exposure and vulnerability to climate-related extreme events and other economic, social and environmental shocks and disasters
SDG 2. End hunger, achieve food security and improved nutrition, and promote sustainable agriculture	2.1: By 2030, end hunger and ensure access by all people, in particular the poor and people in vulnerable situations, including infants, to safe, nutritious and sufficient food all year round
	2.3: By 2030, double the agricultural productivity and incomes of small-scale food producers, in particular women, indigenous peoples, family farmers, pastoralists and fishers, including through secure and equal access to land, other productive resources and inputs, knowledge, financial services, markets and opportunities for value addition and non-farm employment
	2.4: By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality
	2.5: By 2020, maintain the genetic diversity of seeds, cultivated plants and farmed and domesticated animals and their related wild species, including through soundly managed and diversified seed and plant banks at the national, regional and international levels, and promote access to and fair and equitable sharing of benefits arising from the utilization of genetic resources and associated traditional knowledge, as internationally agreed
SDG 3: Ensure healthy lives and promote well-being for all at all ages	3.9 By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination

SDG 6. Ensure availability and sustainable management of water and sanitation for all	6.1: By 2030, achieve universal and equitable access to safe and affordable drinking water for all
	6.3: By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally
	6.4: By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity
	6.5: By 2030, implement integrated water resources management at all levels, including through transboundary cooperation as appropriate
	6.6: By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes
SDG 7. Ensure access to affordable, reliable, sustainable, and modern energy for all	7.1: By 2030, ensure universal access to affordable, reliable and modern energy services
	7.2: By 2030, increase substantially the share of renewable energy in the global energy mix
	7.3: By 2030, double the global rate of improvement in energy efficiency
SDG 8. Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all	8.4: Improve progressively, through 2030, global resource efficiency in consumption and production and endeavour to decouple economic growth from environmental degradation, in accordance with the 10-year framework of programmes on sustainable consumption and production, with developed countries taking the lead
	8.9: By 2030, devise and implement policies to promote sustainable tourism that creates jobs and promotes local culture and products
SDG 9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation	9.4: By 2030, upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes, with all countries taking action in accordance with their respective capabilities
SDG 11: Make cities and human settlements inclusive, safe, resilient and sustainable	11.6: By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management

SDG 11 *(continued)*	11.B: By 2020, substantially increase the number of cities and human settlements adopting and implementing integrated policies and plans towards inclusion, resource efficiency, mitigation and adaptation to climate change, [and] resilience to disasters
SDG 12. Ensure sustainable consumption and production patterns	12.2: By 2030, achieve the sustainable management and efficient use of natural resources
SDG 14. Conserve and sustainably use the oceans, seas and marine resources for sustainable development	14.1: By 2025, prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution
	14.2: By 2020, sustainably manage and protect marine and coastal ecosystems to avoid significant adverse impacts, including by strengthening their resilience, and take action for their restoration in order to achieve healthy and productive oceans
	14.3: Minimize and address the impacts of ocean acidification, including through enhanced scientific cooperation at all levels
	14.4: By 2020, effectively regulate harvesting and end overfishing, illegal, unreported and unregulated fishing and destructive fishing practices and implement science-based management plans, in order to restore fish stocks in the shortest time feasible, at least to levels that can produce maximum sustainable yield as determined by their biological characteristics
	14.5: By 2020, conserve at least 10 percent of coastal and marine areas, consistent with national and international law and based on the best available scientific information
	14.6: By 2020, prohibit certain forms of fisheries subsidies which contribute to overcapacity and overfishing, eliminate subsidies that contribute to illegal, unreported and unregulated fishing and refrain from introducing new such subsidies, recognizing that appropriate and effective special and differential treatment for developing and least developed countries should be an integral Part of the World Trade Organization fisheries subsidies negotiation
	14.7: By 2030, increase the economic benefits to Small Island developing States and least developed countries from the sustainable use of marine resources, including through sustainable management of fisheries, aquaculture and tourism

SDG 15. Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss	15.1: By 2020, ensure the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services, in particular forests, wetlands, mountains and drylands, in line with obligations under international agreements
	15.2: By 2020, promote the implementation of sustainable management of all types of forests, halt deforestation, restore degraded forests and substantially increase afforestation and reforestation globally
	15.3: By 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land degradation-neutral world
	15.4: By 2030, ensure the conservation of mountain ecosystems, including their biodiversity, in order to enhance their capacity to provide benefits that are essential for sustainable development
	15.5: Take urgent and significant action to reduce the degradation of natural habitats, halt the loss of biodiversity and, by 2020, protect and prevent the extinction of threatened species
	15.6: Promote fair and equitable sharing of the benefits arising from the utilization of genetic resources and promote appropriate access to such resources, as internationally agreed
	15.7: Take urgent action to end poaching and trafficking of protected species of flora and fauna and address both demand and supply of illegal wildlife products
	15.8: By 2020, introduce measures to prevent the introduction and significantly reduce the impact of invasive alien species on land and water ecosystems and control or eradicate the priority species
	15.9: By 2020, integrate ecosystem and biodiversity values into national and local planning, development processes, poverty reduction strategies and accounts

Note: SDG 12 on Sustainable Consumption and Production is discussed in Part III - Chapter 1, where all its targets are listed in Box 3. Target 12.2 is also reproduced below because of its central importance to this report. The resource implications of SDG 13 on combating climate change are covered under other SDGs (e.g. SDG 7 on energy).

Source: https://sustainabledevelopment.un.org/?menu=1300

1.1.3. National resource efficiency strategic objectives and targets

If the SDGs and their associated targets are to be met, countries will need to adopt strategic objectives and targets that enable them individually to contribute to fulfilling the SDG aspirations. At present, the most extensive review of countries' strategic objectives and targets relating to resource efficiency has been carried out by the European Environment Agency (EEA, 2011c). Table 13 lists the major strategic objectives that were adopted by 2011 by six or more countries in Europe, where "strategic objective" refers to broad strategic policy goals that have either not been quantified or have no timeline associated with them. In contrast, "targets" are policy goals that are specific, measurable and time-bound.

It is clear that while many of these strategic objectives map closely onto the SDGs, most of them have not yet been adopted by many of the 31 EEA member and cooperating countries. Moreover, when it comes to targets, the coverage is patchier still. The worldwide overview of resource targets by Bahn-Walkowiak and Steger (2015) contains entries for only China, Japan, South Korea, the US and European countries. Of these countries, only China, Japan, Austria, Hungary and Germany have formulated specific targets for increasing resource efficiency or productivity. Within Europe, Germany, Italy, Austria, Romania and Sweden have formulated quantitative targets for material efficiency, while Italy, Austria, Sweden, Switzerland and Hungary have quantitative targets addressing material inputs. The indicators and targets adopted by the Japanese Government in the

Table 13: Strategic objectives in relation to resource efficiency in EEA countries (numbers in brackets are the number of countries with that objective)

- Increasing recycling rates (23)
- Efficient use of natural resources/raw materials (22)
- Improving energy efficiency (19)
- Increasing the share of renewable energy (18)
- Waste prevention/decoupling waste generation from economic growth (18)
- Reducing energy use (17)
- Sustainable forest management (14)
- Halting biodiversity loss (14)
- Reducing water use (13)
- Improving the water quality of natural waters (12)
- Reducing energy use in buildings (12)
- Reducing emissions of air pollutants (11)
- Promoting sustainable consumption and production (11)
- Reducing the use of mineral resources (10)
- Making transport more sustainable (9)
- Sustainable agriculture (9)
- Increasing security of supply of energy and materials (9)
- Promoting green public procurement (8)
- Reducing use of fossil fuels (7)
- Sustainable land use (7)
- Reducing resource use (6)
- Sustainable fisheries (6)
- Protecting groundwater (6)

Source: EEA (2011c) pp. 32–33.

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

context of its plan for a Sound Material-Cycle Society (SMCS) are discussed in more detail in Part IV - Section 1.1.4. As for Europe, in July 2014 the European Commission suggested setting a target to increase EU material resource productivity by 30 percent between 2014 and 2030, implying a doubling in the rate of increase in resource productivity over that period (EC, 2014)[21]. However, this target was not mentioned in the revised proposals for a "circular economy package" that were put forward by a new European Commission in December 2015 (EC, 2015a), following the withdrawal of the 2014 proposals.

Otherwise, countries' main material targets are related to waste reduction and recycling. Targets for energy efficiency and productivity are more common, but are still far from the ambition that will be required to bring the COP21 2°C global warming target within reach. UN Environment (2015a, p. xviii) reports that even with full implementation of the unconditional INDCs,[22] global emissions in 2030 will still be 14 $GtCO_2e$ above the 42 $GtCO_2e$ median emission level of scenarios that have a greater than 66 percent chance of keeping the global average temperature increase to below 2°C by the end of the century. This falls to 12 $GtCO_2e$ if the conditional INDCs are also implemented.

Policymakers tend to adopt targets for those issues and policy areas that they consider to be important, as the SDG process has shown. Monitoring against these targets then enables progress on these issues to be judged. Targets and indicators have been adopted for the SDGs. What is now required are policies to achieve them, at both national and subnational levels.

1.1.4. Case study: indicators and targets for Japan's Sound Material-Cycle Society (SMCS)

In order to quantify the "Do more with less" concept underlying resource efficiency, Japan and the EU (among others) have proposed and used indicators of resource productivity or resource efficiency. In Japan, DMI (Direct Material Input) was adopted, whereas in the EU, DMC (Domestic Material Consumption: DMI minus exports) was adopted. Both DMI and DMC are metrics of the direct quantity of material inflows to national economies (with DMI more related to production, and DMC related to consumption). As such, they do not take into account the indirect material flows in traded goods resulting from upstream processes such as mining and raw material processing in foreign countries. This has led to the development of the Raw Material Equivalent (RME) indicator.[23] As this report has already discussed, comparing DMI/DMC-based indicators with those based on RME helps raise awareness of the significance of indirect resource flows associated with many low-quantity, high-value substances.[24] This can encourage the 3Rs in respect of these substances, as well as reducing massive wastes.

In Japan, three material flow indicators were adopted with numerical targets in its first Fundamental Plan for Establishing a Sound Material-Cycle Society (SMCS) in 2003. The initial set of indicators comprised: resource productivity (GDP/input of natural resources (DMI)); cyclical use rate (quantity recycled/quantity recycled + natural resources input (DMI)); and final disposal to landfill. This Japanese set of material flow indicators and targets was revised and extended in 2008 and

21 A corrected version of this Communication was issued in September 2014 with the reference COM(2014) 398 final/2.
22 The INDCs (Intended Nationally Determined Contributions) are the commitments to the reduction of GHGs, or to reduced carbon and intensity of their economies, made by countries in the context of the Paris Agreement on climate change emerging from the 2015 Conference of the Parties to the UN Framework Convention on Climate Change (COP21).
23 See Box 1 for a definition of these terms.
24 For example, the RME factor (kg RME/kg metal content) for world gold production over 2000–2010 has been estimated to be between 400,000 and 500,000 (IFEU 2012, Figure 22, Annex 4, p. 20). Reference: IFEU (Institute for Energy and Environmental Research) 2012 'Conversion of European Product Flows into Raw Material Equivalents', final report of the project 'Assistance in the development and maintenance of Raw Material Equivalents conversion factors and calculation of RMC time series' (commissioned by Eurostat), May, http://www.ifeu.de/nachhaltigkeit/pdf/RME_EU27-Report-20120618.pdf.

Part IV: Resource use and resource efficiency in the future

2013, with periodic updates of the Plan itself. A mandated annual review using these indicators provides an opportunity to examine whether SMCS policy delivers successful outcomes. At the same time, through the review, shortcomings of indicators have also been pointed out. This has led to supplementary indicators, with or without a target, being introduced.

Table 14 shows the 2020 targets for these indicators and progress towards them since 1990. The total final disposal to landfill target for 2020 has already been surpassed. Under the other two indicators, resource productivity and cyclical use rate, the 2020 targets have not yet been achieved but good progress is being made towards them. The table also indicates progress in relation to targets for two "supplementary indicators", as well as for an "indicator to monitor changes", which does not have a target. This last indicator is resource productivity measured on an RME basis, as opposed to DMI basis, as in the main indicator. As noted above, comparing DMI with RME productivity measures (the first row and the last row in Table 14) helps raise awareness of the significance of indirect resource flows. Comparing the figures for 2012 with the 2000 baseline shows that DMI-based productivity

Table 14: Development of material flow indicators

Fiscal year		2020 (Target year)	1990	2000	2005	2010	2011	2012	2013	vs.2000
Resource productivity	10,000 yen/tonne	46	-	24.8	30.8	37.6	38.6	38.2	37.8	+53%
Cyclical use rate	%	17	7.4	10	12.2	15.3	15.2	15.2	16.1	+6.1
Final disposal amount	Total (million tonnes)	17	109	56	31	19.2	17.4	17.9	16.3	-71%
	Municipal waste (million tonnes)	-	20	12	8	5	5	5	5	-62%
	Industrial waste (million tonnes)	-	89	44	23	14	12	13	12	-73%
(Supplementary indicator) Resource productivity excluding construction minerals	10,000 yen/ tonne	68	-	54.9	57.6	60.4	60.8	60.2	60.4	+10%
(Indicators to monitor changes) Resource productivity in terms of RME (Raw Material Equivalent)	10,000 yen/ tonne	-	-	18.3	21.5	23.8	23.6	23.7	-	-

Source: Ministry of Environment Japan, 'Fundamental Plan for Establishing a Sound Material-Cycle Society', May 2013, Table 2, p. 6, http://www.env.go.jp/en/recycle/smcs/3rd-f_plan.pdf, updated with a personal communication from Yuichi Moriguchi, April 24 2016.

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

has increased by 54 percent; when measured on an RME basis it is only 30 percent. This indicates the weight of raw materials extracted outside Japan that lie behind Japanese imports of processed or finished goods.

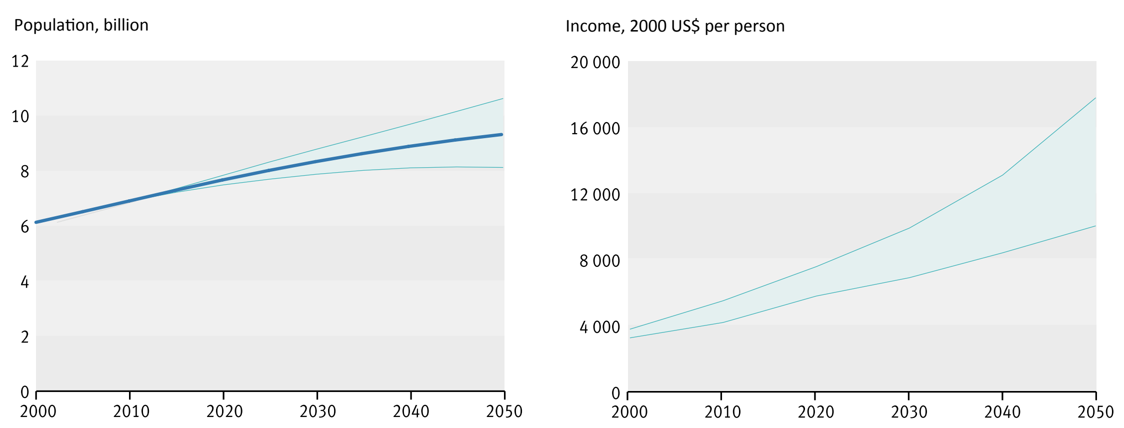
1.2. Conventional and sustainable worlds

Table 11 and Table 12 have set out global aspirations, and in some cases agreed associated targets, for natural resources and the environment. However, responses to convert these global targets into targets and associated policies at the national level have been at best mixed, as shown by Table 13, in the case of the EEA countries. The result is that based on current trends, the global aspirations and targets are very far from being met, as this section, drawing on the GEO-5 (UN Environment, 2012b) "conventional worlds" and "sustainable worlds" scenarios, will show. The construction of such scenarios requires many assumptions and data inputs which are described in GEO-5, but space precludes their inclusion here. The rest of this section intends to give a broad overview of the kinds of differences in resource use and environmental impacts across different themes, which could arise from the kinds of resource efficiency initiatives and policies that have been discussed elsewhere in this report. Two of the main drivers of resource use are population and economy activity, and it is with these that the consideration here of the GEO-5 scenarios begins.

1.2.1. Population and economic activity

The first important point to note for projections of resource use and environmental impacts is that the human population and its economic activity are projected to grow substantially through to 2050, as shown in Figure 100. It may be seen that income is expected to grow relatively much more than population and therefore, without decoupling, will contribute proportionately more to increased resource use and environmental impacts. The projected growth of both population and income takes no account of the risks of disruption and crisis associated with a failure to achieve resource and environmental decoupling at the scale necessary for human activity to return to and remain within the planet's 'safe operating space', as discussed in Part II - Chapter 1.

Figure 100: Projections of population and income growth through to 2050



Note: The shaded areas indicate the 10-90th percentile literature range.

Source: (GDP) van Vuuren et al. 2012; (population) UNDESA 2009

Source: UNEP (2012b) Figure 16.4, p. 427.

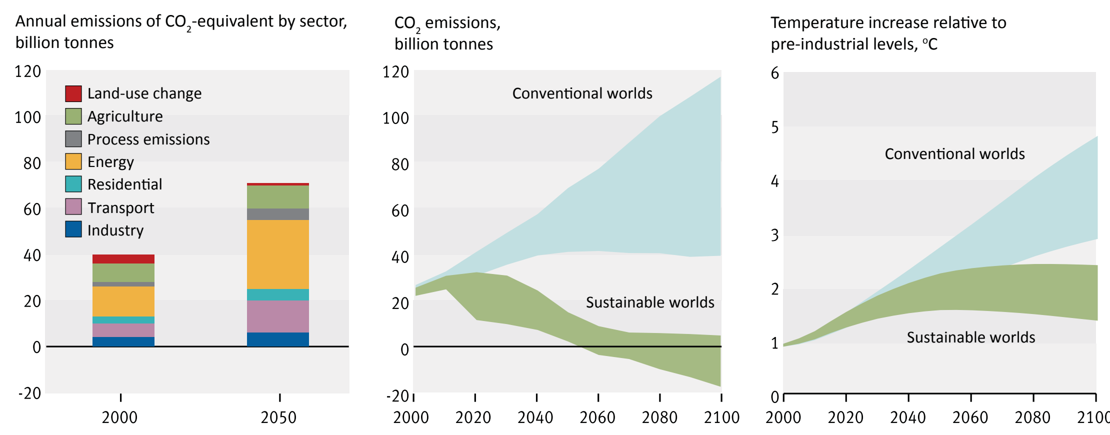
Part IV: Resource use and resource efficiency in the future

These projections are common to the UN Environment's scenario characterization of both "conventional" and "sustainable" worlds in GEO-5 (UN Environment, 2012b).

1.2.2. Climate change and energy

The first implication of these projections of population and economic growth is that based on current trends, human use of energy and

Figure 101: Projections of greenhouse gas emissions in different scenarios

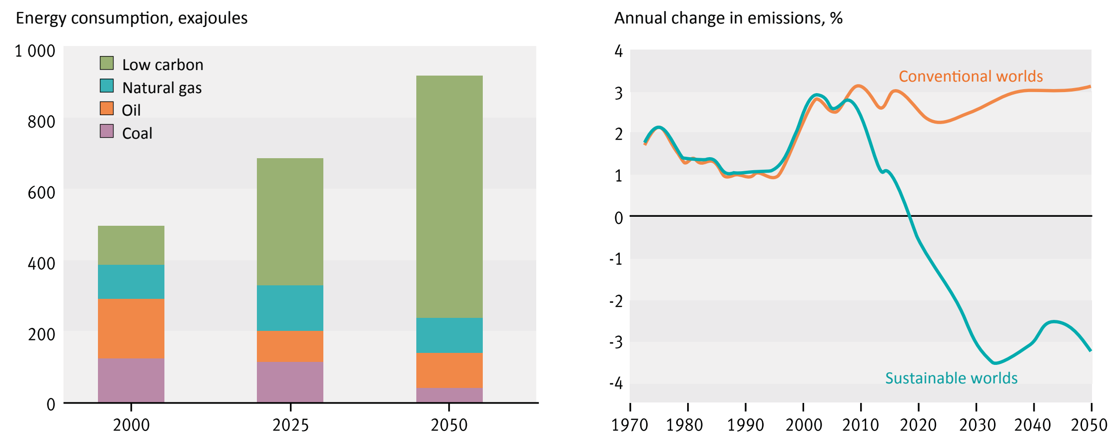


Note: Emission and temperature scenarios cover a longer time period than other scenarios in this chapter because of inertia in the climate system. The shaded areas indicate the 10-90th percentile literature range.

Source: van Vuuren et al. 2008a, 2008b; Fisher et al. 2007

Source: UNEP (2012b), Figure 16.5, p. 429.

Figure 102: An example of growth in low-carbon energy sources and corresponding required emission reductions for a "sustainable world"



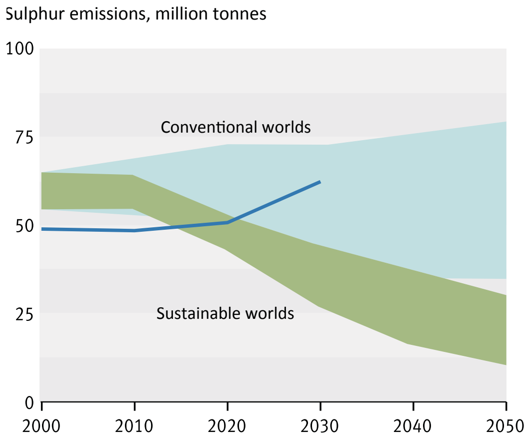
The category Low carbon refers to renewable energy, nuclear power and fossil fuels in combination with carbon capture and storage and efficiency, and illustrates the level of transition required. Different models and studies suggest different combinations

Source: PBL 2009

Source: UNEP (2012b) Figure 16.7, p. 431.

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

Figure 103: Sulphur emissions reductions consequent on a stringent climate policy



Conventional world scenarios include those without climate policy; sustainable world scenarios include those with stringent climate policy. The blue line represents the scenario under current legislation.

Note: The shaded area indicates the 10-90th percentile literature range.

Source: Van Vuuren et al. 2008a; Cofala et al. 2007

Source: UNEP (2012b), Figure 16.6, p. 429.

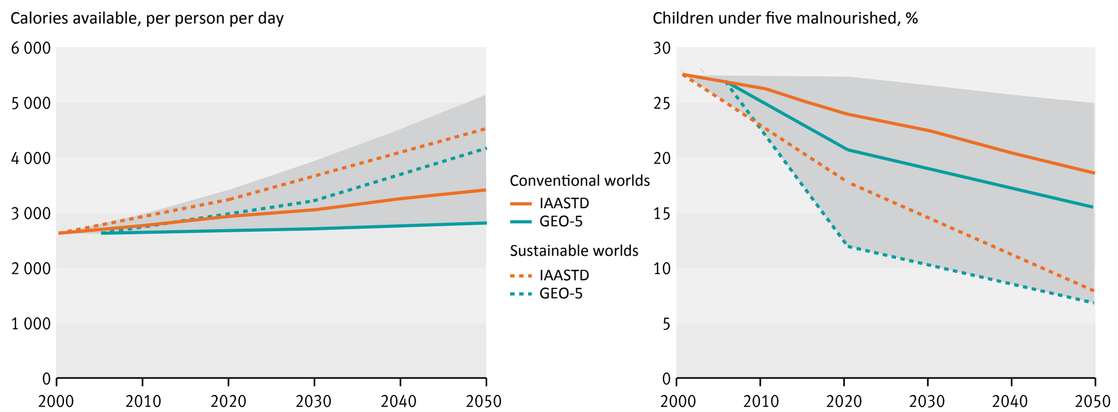
its resulting emissions will increase greatly by 2050. Figure 101 shows projected GHG emissions by sector and overall, with the associated global average temperature increase, for both "conventional" and "sustainable" worlds. Shifting to the "sustainable worlds" trajectories will require very great increases in energy efficiency, and an almost total shift from fossil fuels to zero- (or negative) emission energy sources, as shown in Figure 102.

A co-benefit of a climate policy shift to a sustainable world would be a very large reduction in local air pollution, including sulphur emissions, as shown in Figure 103, with enormous related health benefits.

1.2.3. Land and food

It is obviously important that food availability grows alongside the projected population growth. SDG 2 also envisages the distribution of that food so that no one is undernourished. Figure 104 suggests that it is possible to increase the supply of food sustainably, and distribute it such that child malnourishment is much reduced.

Figure 104: Food availability under different scenarios



Note: Scenarios selected from GEO-4, the IAASTD study and the Millennium Ecosystem Assessment are those that most reflect the sustainable and conventional worlds on the basis of storyline or quantitative elaboration. The shaded area shows the range in the literature. *GEO-5* results as discussed in box 16.2.

Source: Hughes et al. 2011; IAASTD 2009a; UNEP 2007; FAO 2006b; MA 2005a

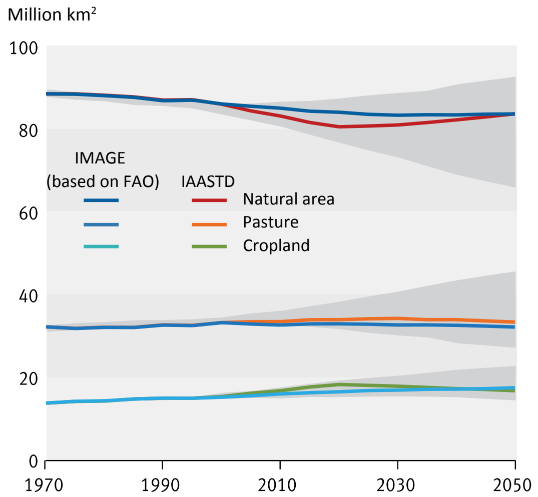
Source: UNEP (2012b), Figure 16.8, p. 433.

However, as Part II - Chapters 1 and 2 of this report have made clear, there is very little scope for expanding the food supply by increasing the area of land under cultivation, if the targets for the conservation of forests and biodiversity set out in Table 11 and Table 12 (SDG 15) are to be met. This means that agricultural practices, and the associated food system, will have to become more efficient, less wasteful and more productive, to meet growing nutritional demands from the same amount of land or less, and to do so sustainably. Agricultural land use will need to develop in accordance with the lower levels of the ranges shown in Figure 105.

1.2.4. Cities

Part III - Chapter 3 of this report showed that one of the key emerging mega-trends is rapid urbanization in emerging and developing economies. Figure 106 shows the projected growth of the urban population over 1950–2050. With such levels of growth, it is likely

Figure 105: Agricultural land-use projections under different scenarios

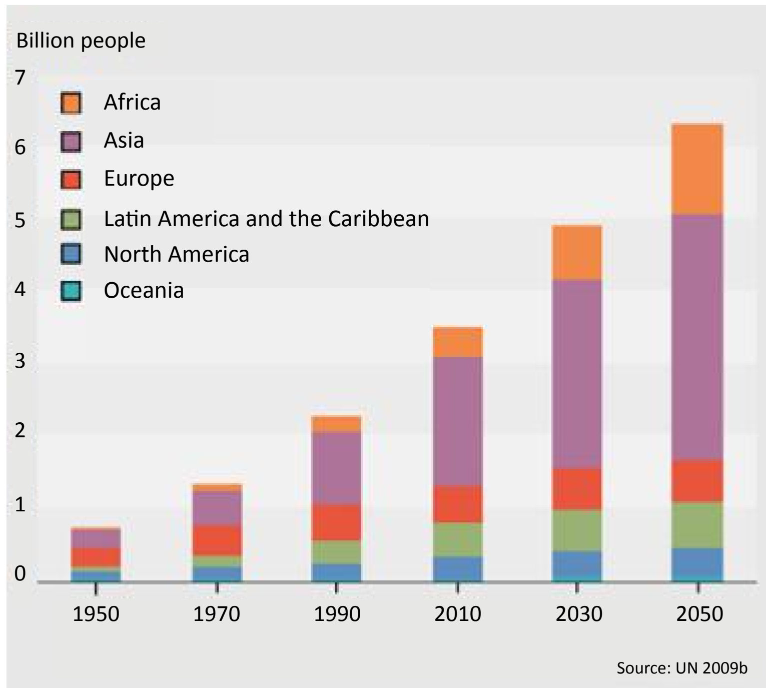


Note: Shaded area indicates 10–90th percentile literature range

Source: Rose et al. 2012; Hurtt et al. 2011; Smith et al. 2010; IAASTD 2009a; OECD 2008a; UNEP 2007; FAO 2006; MA 2005a

Source: UNEP (2012b), Figure 16.6, p. 429.

Figure 106: Projected urban population growth



Source: UNEP (2012b) Figure 1.2, p. 8.

that much more resource-efficient models of urban development will need to be pioneered and implemented if SDG 11, and many other resource- and environment-related SDGs, are to be met.

1.2.5. Water

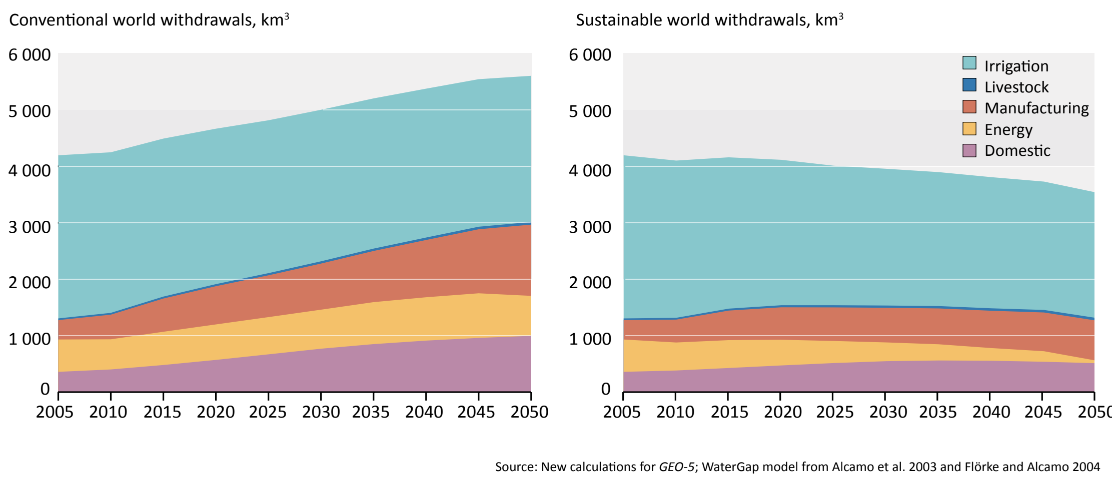
Many people, including about 1.5 billion in Asia, are already experiencing water stress. Yet, growing populations, economies, food supply and cities will all make further demands on the world's freshwater resources. As with land, the only way the demand for water services can be sustainably met in the future is through its far more efficient and productive use.

Figure 107 shows various projections of water use in "conventional" and "sustainable" worlds. With water use developing as in the "conventional" projections, water stress could affect 3.9 billion people by 2050 (UN Environment, 2012b, p. 437), with many of these lacking secure access to safe drinking water and sanitation. While levels of water stress even in "sustainable" scenarios remain significant (see UN Environment (2012b), Figure 16.12, p. 438), the greater resource efficiency in these "sustainable" worlds means that the proportion of the global population without access to safe drinking water in 2050 could diminish to 3–5 percent (from 23 percent in 2000) and without access to sanitation to 15–18 percent (from 51 percent in 2000).

1.2.6. Forests and biodiversity

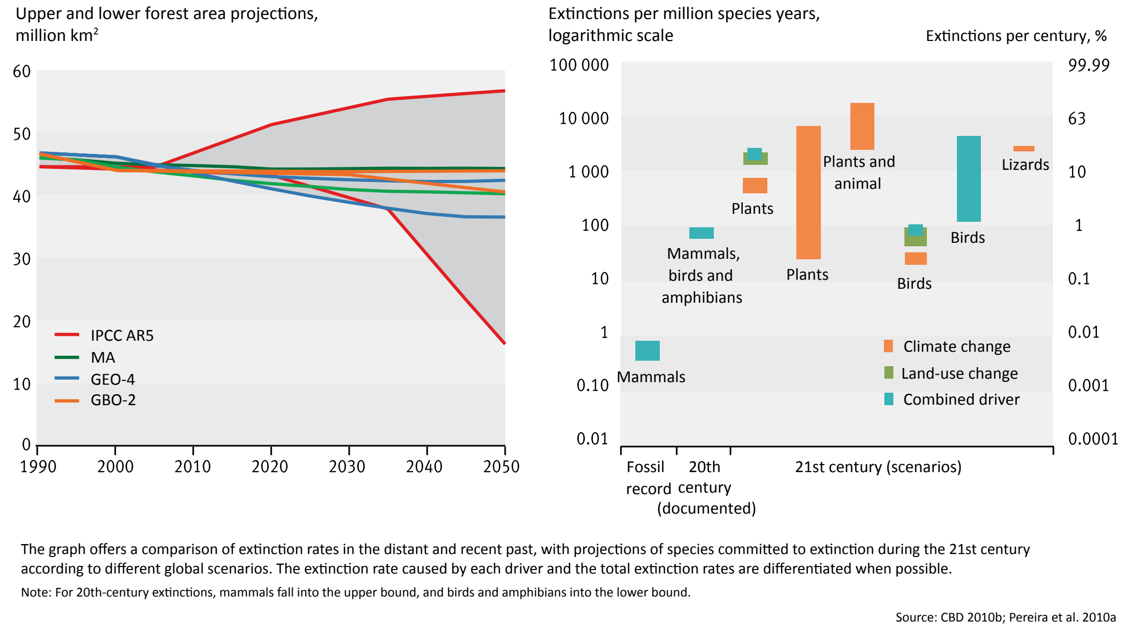
Conserving forests, especially tropical forests, and biodiversity go hand in hand. Figure 108 shows the extent of forest area that is projected in different global scenarios, and the corresponding species extinctions. The figure shows that climate change could lead to the extinction rate increasing by two or three orders of magnitude over the fossil record, making reducing climate change a major priority for reducing biodiversity loss. Aside from this, UN Environment (2012b, Figure 16.14, p. 440) shows that the most effective means of reducing biodiversity loss is changing to healthy diets and sustainably increasing agricultural productivity, in order to avoid the loss of natural areas to agriculture.

Figure 107: Projections of water withdrawals by sector under different scenarios



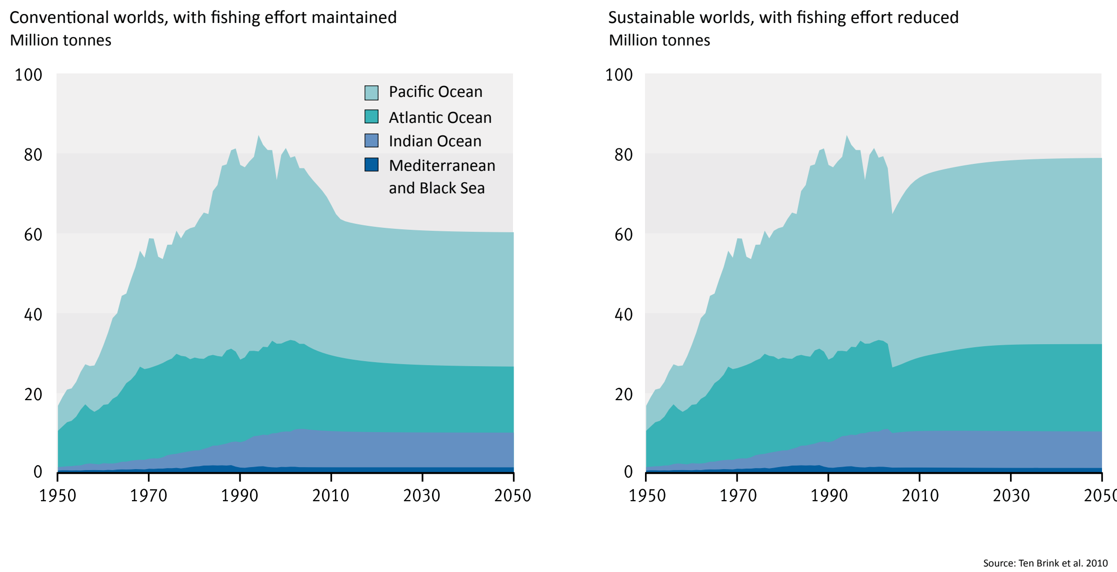
Source: UNEP (2012b) Figure 16.11, p. 437.

Figure 108: Changes in the extent of forest up to 2050 in different global scenarios, and estimated rates of species loss



Source: UNEP (2012b), Figure 16.13, p. 439.

Figure 109: Marine catches with and without a reduction in fishing effort, 1950–2050



Source: UNEP (2012b), Figure 16.15, p. 441.

1.2.7. Fisheries

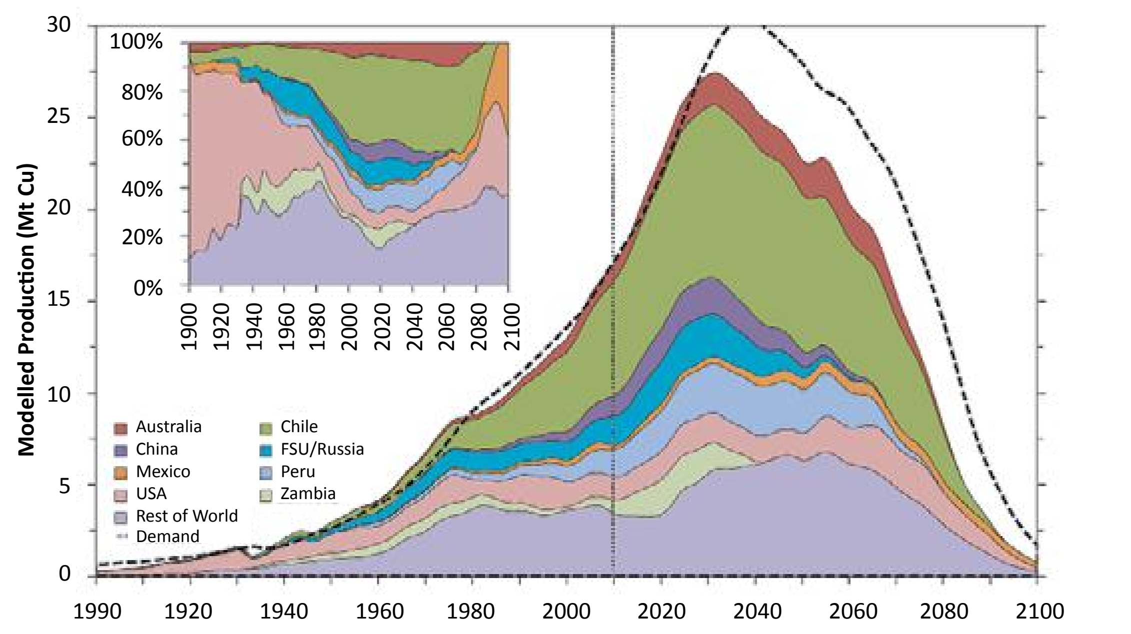
The world's ocean fisheries are among the least efficiently exploited, from economic, resource and environmental points of view. Excess fishing capacity has driven yields below maximum sustainable yields, such that the annual catch is considerably below what it could be. Figure 109 shows that reducing fishing effort, while leading to a short-term drop in yields, could lead to substantially higher catches in the future. This is provided that other threats to fish stocks, such as ocean acidification, eutrophication, temperature change and loss of mangrove forests, do not prevent this.

1.2.8. Metals and minerals

The extraction and use of metals and minerals has greatly increased over the last half-century. Since many features of improved lifestyles (housing, infrastructure, transportation, communications, etc.) involve metals and minerals, it is virtually certain that demand for them will continue to grow in the coming decades. It is less certain, however, that supply will meet this increased demand. In this regard, a recent study for copper (Figure 110) shows historic (1900–2010) and projected (2010–2100) supply (coloured areas) and demand (the dashed line). These results suggest that supply may become insufficient by 2030 or thereabouts, potentially constraining aspects of global development, especially for the less affluent. Similar analyses for other metals are yet to be carried out, but are a high research priority given the obvious policy implications of potential supply limitations. In the case of the projections shown in Figure 110, these outcomes could be mitigated through greater recycling of anthropogenic stocks of copper. Greater recycling more generally has an important role in increasing the resource efficiency of societal metal use (UN Environment, 2013c).

With regard to non-metallic minerals, UN Environment (2014d) reports that the current

Figure 110: Global copper production by country and region (coloured areas) and historical and anticipated demand (dashed line)



Source: Northey et al. (2014).

use of sand greatly exceeds natural renewal rates, and, together with gravel, the amount being mined is increasing exponentially. This is mainly a result of rapid economic growth in Asia (UN Environment and CSIRO (2011), cited in UN Environment (2014d)) and the consequent demand for cement, production of which increased threefold between 1994 and 2014. This has caused serious environmental impacts, especially on the river and marine ecosystems from which the sand is often mined. Clearly, resource efficiency could play a major role in reducing these impacts through the optimized use of existing resources, the recycling of demolition waste, and the use of sand substitutes where possible.

1.3. Conclusions on projections and the SDGs

It is clear from the previous section that the "conventional worlds" projected on the basis of the continuation of current trends will not come anywhere near meeting the aspirations and targets of the SDGs shown in Part IV - Section 1.1, even in 2030, let alone by 2050. In fact, continuation of current trends will take the world further and further away from the resource and environmental targets of the SDGs. Such continuation may not even prove possible given the threats to the environment and its resources, and thus to the economy, to which they are giving rise.

In contrast, the GEO-5 "sustainable worlds" scenario (key aspects of which are summarized in the previous section) shows that meeting the SDG aspirations and targets, based on projections of the same levels of population and economic growth as the "conventional worlds" scenario, and with current technologies, is possible. Nevertheless, its achievement will require sweeping changes to patterns of both production and consumption, such as those described in Part III - Chapter 6.

However, there is evidence that it would be a mistake for policymakers to pursue the SDGs individually, in silos. Given the strong interactions between some of the issues covered by the SDGs, some strategies to achieve a particular SDG may make other SDGs difficult or even impossible to achieve. Integrated strategies that focus on achieving a number of SDGs together can lead to better collective outcomes.

Research conducted at IIASA (the International Institute for Applied Systems Analysis) for the International Resource Panel (UN Environment, 2015f) has sought to identify some of the more difficult trade-offs in the pursuit of multiple SDGs, by examining the tensions that competition for resources creates between food security and environmental conservation. Restricting land-use change can mitigate deforestation and associated GHG emissions, habitat destruction and biodiversity loss, and reduce reliance on fertilizers. However, these policies can also ultimately limit the land available for agriculture and reduce the production of food and other crops. This can result in any or all of the following: expansion of irrigation, decreased availability of food and increased food prices.

Strong restrictions on land-use change, therefore, support natural resource conservation, but require additional parallel investments in resilient and productive agricultural systems to maintain food security. Such studies, by identifying complex interdependencies, allow general conclusions to be drawn about how to avoid zero-sum outcomes in which policies designed to achieve one SDG jeopardize the attainment of others. Coherent mixes of policies are often needed to ensure positive net environmental and development outcomes in complex situations. Based on its analysis of such resource nexus issues, it is possible to classify policy strategies for SDG implementation into three groups:

The first set of strategies increases pressure on land and human systems, resulting in a net deterioration of progress towards the larger SDG agenda. In many cases, policies designed to target a subset of the SDGs result in a disproportionate increase in the challenges facing other sectors, putting some SDGs further out of reach. Siloed approaches — in which individual issues are carved from the whole and pursued as if in a vacuum — risk falling into this category, as such policies' impacts on resource availability can often be counterproductive in the context of larger agendas. For example, ambitious bioenergy production and biodiversity conservation measures impose costs or restrictions on food, feed and fibre-production systems. These costs can compromise food security in the short term and the feasibility of additional conservation initiatives in the long term. Therefore, strategies limited to a series of interventions targeted at single SDGs may forestall growing challenges in some sectors, but will generally fail to provide comprehensive, lasting solutions.

Strategies in the second category neither increase nor reduce total pressure on land resources. Policy options in this category cannot eliminate trade-offs among sectors and goals, but they do allow for prioritization among competing demands and targets. This supports systems in danger of failing, without disproportionately increasing the burden on other sectors. As environmental policies such as GHG pricing and moderate forest-conservation measures have a minimal pressurizing effect on land systems, they should therefore be pursued as first steps towards broader SDG implementation, being careful to avoid unwanted social impacts.

The third set of possible SDG strategies reduces pressure on the land system, largely through the adoption of Sustainable Consumption and Production (SCP) policies. This set escapes zero-sum outcomes and generates progress towards multiple, diverse goals by identifying effective regional, targeted interventions that also constructively advance the larger SDG agenda. For instance, decreased reliance in developed regions on meat and other animal products for protein can reduce mortality and other health impacts of over-consumption. At the same time, this will increase availability of these land- and water-intensive commodities in developing and undernourished regions, reducing mortality and enabling progress towards food security for all (SDG2).

Increasing resource efficiency cannot be expected to achieve the SDGs all by itself, nor can it resolve all possible compromises and trade-offs between different SDGs. Nonetheless, the next section, based on new modelling carried out for this report, shows that it can improve outcomes very substantially over projections based on current trends. Increasing resource efficiency can therefore make a considerable contribution to achieving the SDG aspirations and targets to which the global community is now committed.

2. ASSESSING THE POTENTIAL AND BENEFITS OF RESOURCE EFFICIENCY, AND SYNERGIES WITH AMBITIOUS ACTION ON CLIMATE CHANGE

2.1. Introduction: assessing the potential and benefits of resource efficiency

The world has shifted from worrying about sustainability to committing to constructive action. The SDGs represent a high level of international commitment and include a sound understanding of the natural resource and ecosystem health underpinnings of achieving economic development and human well-being in the future.

In June 2015, the G7 leaders committed "to take ambitious action to improve resource efficiency" (G7, 2015, p. 17) and called for "urgent and concrete action ... to address climate change ... in line with the global goal to hold the increase in global average temperature below 2°C" (G7, 2015, p. 14–15). At the Paris COP21 in December 2015, the world agreed to a process to deliver on that goal.

As already noted, the G7 leaders also asked the International Resource Panel to advise on the potential and most promising solutions for achieving resource efficiency. As part of the response to that request, the International Resource Panel commissioned new modelling to explore the potential synergies and trade-offs between limiting global average temperature increases to 2°C, and achieving substantial increases in resource efficiency. This chapter reports on the results of that modelling.

The modelling was carried out using an integrated multimodel framework to explore potential future pathways for global resource use, GHG emissions, and economic activity to 2050. This allows us to assess the potential for — and economic impacts of — ambitious action to improve resource efficiency and address climate change. The modelling framework is described in an appendix to this chapter (Part I - Section 2.7). Further discussion of the modelling presented here is also provided by Hatfield-Dodds et al. (2017).

The headline result from the modelling is that G7 nations and the world can make substantial progress on each of these two agendas, but the best outcomes come from pursuing resource efficiency and ambitious emissions reductions together.

2.2. Summary of key findings

The main finding is that there is substantial potential to achieve economically attractive resource efficiency that provides win-win outcomes; reducing environmental pressure while increasing incomes and economic growth. These impacts differ from the *Existing Trends* scenario, which projects that natural resource use will increase from 85 billion to 186 billion tonnes over the 35 years to 2050, reflecting a 28 percent increase in population and a 71 percent increase in per capita resource use.

Specific findings include that resource efficiency policies and initiatives could:

- reduce per capita natural resource use globally by 28 percent in 2050 relative to *Existing Trends*, when combined with ambitious global action on climate change; and stabilize per capita resource use at current levels in G7 countries
- reduce GHG emissions by up to 20 percent in 2050 compared with *Existing Trends*, with global emissions falling to 63 percent below 2015 levels and G7 emissions falling to 74 percent below 2015 levels by 2050, in combination with ambitious greenhouse abatement policies
- more than offset the near-term economic costs of ambitious climate action, so that income is higher and economic growth is stronger than in the *Existing Trends* (Reference) scenario
- deliver annual economic benefits of more than US$2,000 billion globally in 2050 relative to *Existing Trends*, including benefits of US$600 billion in G7 nations, while also helping put the world on track to limit global warming to 2°C or lower.

The finding that resource efficiency measures can boost economic growth, as well as reduce environmental pressure, is consistent with economic theory and practical experience (see Part II - Chapter 3). It should nevertheless be noted that despite the novelty of this work, many of the caveats and assumptions around the results that were noted in Part II - Chapter 3 (especially around the examples of CGE modelling cited there) also apply. While the authors consider that the projected resource efficiency gains can be treated as a reasonable minimum (or "lower bound") estimate of their economic potential, more confidence should be placed in the direction of the specific findings than in their absolute value. In practice, the level and mix of economic and environmental benefits achieved will depend on the detail of the policies and approaches implemented. This suggests that an efficient suite of resource efficiency measures will need to be developed and tested for use across different contexts.

More details of the modelling framework and representation of resource efficiency measures and emissions reduction policies are provided below and in the appendix to this chapter (Part IV - Section 2.7).

2.3. Scenarios considered in this assessment

The analysis is based on four core scenarios, each representing a specific combination of potential future resource use trends and future GHG emissions pathways, as shown in Figure 111.

Existing Trends is calibrated to historical trends in per capita resource use, across major world regions, accounting for changes in income and GDP per capita. GHG emissions are calibrated to RCP6.0, one of four benchmark trajectories for climate forcing used by the IPCC, which is broadly consistent with the Paris pledges (INDCs) to 2030. This emissions pathway is consistent with global temperatures increasing by around 3°C by the end of this century, and rising to around 4°C thereafter (Rogelj et al., 2012).

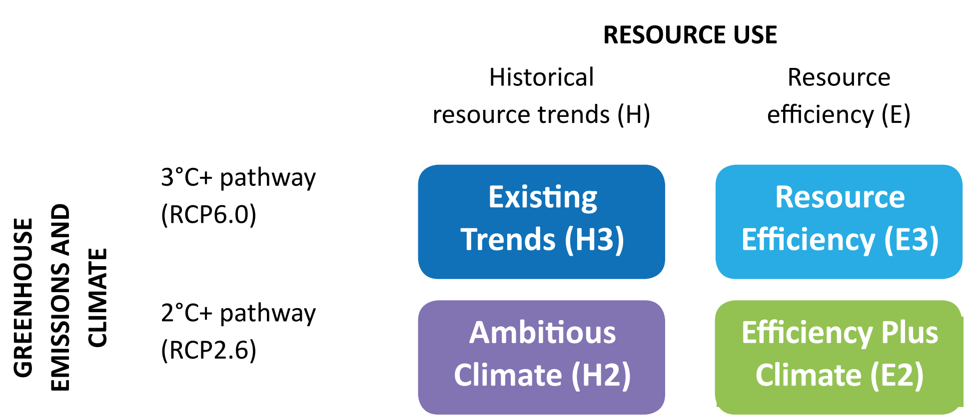
Resource Efficiency assumes a package of innovations, information, incentives and regulations to promote ambitious but achievable increases in resource efficiency, and reductions in total resource extractions, in combination with the same greenhouse policy settings as *Existing Trends*.

Ambitious Climate assumes that resource use follows historical trends, but that the world shifts decisively to a 2°C climate pathway, involving more ambitious emissions reductions. The modelling imposes stylized global abatement policies that are calibrated to achieve global emissions that match cumulative emissions in RCP2.6 to 2050. This is the lowest of the four IPCC benchmark trajectories, with around a 50:50 chance of limiting temperature increases to 2°C above pre-industrial levels.

Efficiency Plus combines the settings for the *Resource Efficiency* and *Ambitious Climate* scenarios to explore potential policy interactions. Synergies between these policies deliver larger reductions in resource use and larger reductions in GHG emissions. This implies a higher chance of limiting global warming to 2°C or lower, as well as larger reductions in other environmental pressures associated with resource use. Economic outcomes fall between those projected for the Resource Efficiency and Ambitious Climate scenarios, with stronger economic growth than in *Existing Trends*.

The scenarios are also related qualitatively to the common Shared Socioeconomic Pathways (SSPs).

Figure 111: Scenarios for assessing resource and climate futures



Source: Project team.

Existing Trends aligns to SSP2, described as "middle of the road", while Efficiency Plus aligns to SSP1, described as "sustainability" / "taking the green road" (O'Neill et al., 2015, IIASA, 2015).

2.4. Key findings: outcomes for G7 nations

2.4.1. G7 resource efficiency and natural resource use

The modelling suggests that there is substantial potential to achieve economically attractive resource efficiency, thereby reducing resource use and boosting economic growth across G7 nations and globally.

Under *Existing Trends*, per capita resource use in G7 nations is projected to increase from 22 tonnes per capita in 2015 to 37 tonnes per capita in 2050.[25] Resource efficiency could reduce material extractions in G7 countries by up to 22 percent relative to *Existing Trends* by 2050. Meanwhile, resource efficiency combined with ambitious emissions reductions would see G7 resource use per capita stabilize around current levels until 2050, 31 percent below *Existing Trends*, while GDP per capita grows by 53 percent per person. The *Ambitious Climate* scenario reduces resource use in G7 nations by 15 percent below *Existing Trends* in 2050, all else being equal (Figure 112).

2.4.2. G7 greenhouse gas emissions

The *Existing Trends* scenario assumes that the COP21 Paris pledges are fully implemented, but does not account for the Paris commitments to a virtuous cycle of reviews and more ambitious future pledges. GHG emissions from G7 countries are thus projected to increase by 17 percent from current levels by 2050.

The combination of resource efficiency and global climate action could see G7 emissions fall by 74 percent from current levels by 2050, compared with a 68 percent reduction in emissions without resource efficiency. Resource efficiency policies alone reduce annual GHG emissions from

Figure 112: G7 Resource Use (DMC) per capita

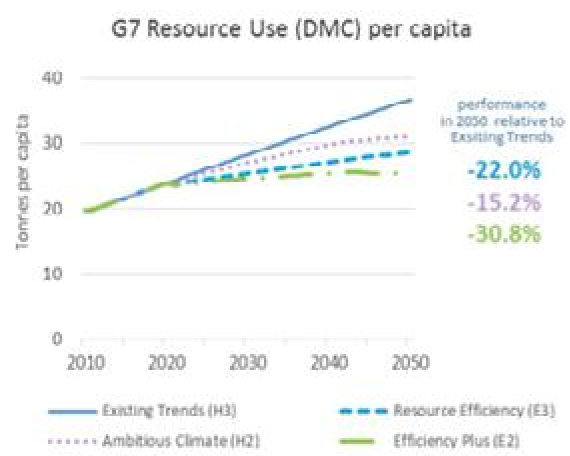
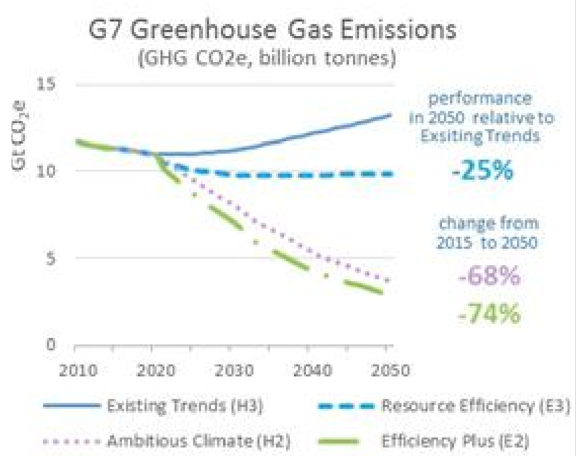


Figure 113: G7 Greenhouse gas emissions



25 Resource use in this modelling is measured by Domestic Material Consumption (DMC), which represents the "amount of materials used by an economy and is defined as the quantity of raw materials extracted from the domestic territory, plus all physical imports minus all physical exports." http://ec.europa.eu/eurostat/statistics-explained/index.php/Glossary:Material_flow_indicators

G7 nations by up to 25 percent by 2050, relative to *Existing Trends* (Figure 113).

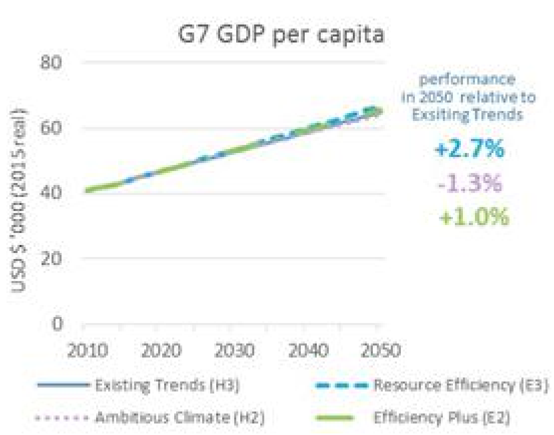
2.4.3. G7 economic performance and synergies

Resource efficiency provides net economic benefits, both for G7 nations and at the global scale, boosting economic growth. These gains are driven by innovation to achieve more efficient natural resource use, along with increases in investment reflecting lower natural resource cost of consumption.

In the resource efficiency plus climate action scenario (Efficiency Plus), the stronger economic growth from resource efficiency outweighs the slower medium-term economic growth associated with ambitious global action on climate change. This results in Efficiency Plus achieving stronger economic growth than the *Existing Trends* scenario. GDP across the G7 nations is US$600 billion higher in 2050 (US$600 per person, or 1.0 percent) in the Efficiency Plus scenario, relative to *Existing Trends*, and US$1,700 billion higher (US$1,750 per person, or 2.7 percent) in the Resource Efficiency scenario (Figure 114).

Achieving these economic benefits will require governments and businesses to take action to overcome market failures and other barriers to resource efficiency, and to promote innovation and improvements in the extraction, use and disposal of materials (see Part II - Chapter 3). A key finding of the analysis is that different types of policies have different economic and environmental effects, thus different policy mixes will result in different overall outcomes. One important example of this is in relation to the "rebound effect": the phenomenon whereby improvements in efficiency reduce the unit cost of a resource, thereby increasing demand for and consumption of that resource (as discussed in Part II - Section 3.3.4). Indeed, the modelling shows that innovation to improve resource efficiency typically reduces unit costs, which boosts not only economic growth but also total resource use — in other words, the "rebound effect" occurs.

Figure 114: G7 GDP per capita



The modelling balances this potential for a rebound effect with the application of two other policy elements: a resource extraction tax, which reduces resource use but also partially dampens economic growth; and regulations and new information (to overcome information failures and split incentives), which reduce resource use while boosting economic growth modestly. The importance of each of these policy elements in the modelling emphasizes that a suite of policy instruments will be needed to maximize the benefits of resource efficiency. In practice, business and government actions will also involve a range of upfront costs and expenses, in order to achieve the benefits of resource efficiency over the longer term. As discussed in Part II - Chapter 3, these costs and expenses are notoriously difficult to include in modelling analyses of this kind, and have not been fully accounted for in this exercise. If they proved to be significant, this may reduce the economic benefits delivered by resource efficiency reported above.

2.5. Key findings: outcomes for the world as a whole

The overall global findings are consistent with the findings for G7 nations, accounting for stronger

Part IV: Resource use and resource efficiency in the future

Figure 115: Global resource use (DMC) per capita

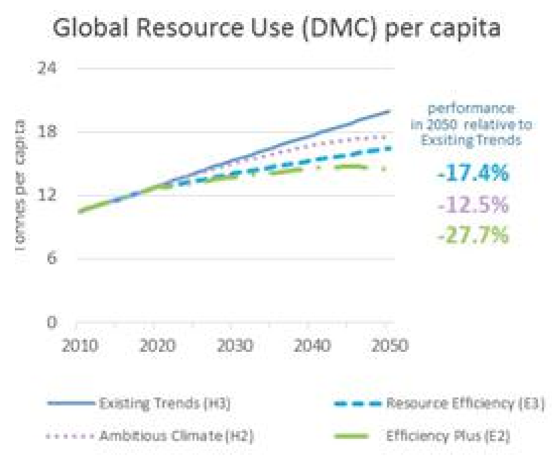
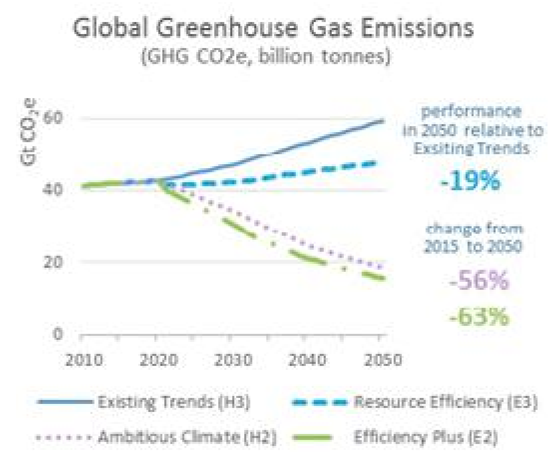


Figure 116: Global greenhouse gas emissions



underlying growth in population, resource use, greenhouse gas emissions, and economic activity.

2.5.1. Global resource efficiency and use

Global resource use under *Existing Trends* is projected to grow from 12 tonnes per person to 20 tonnes per person by 2050. Improved resource efficiency could limit this growth to 17 tonnes per person in 2050, representing a 17 percent reduction from *Existing Trends*. Action to reduce GHG emissions also reduces natural resource use by 12 percent in 2050, all else being equal. Further, the Efficiency Plus scenario reduces per capita resource by 28 percent relative to *Existing Trends* (Figure 115).

2.5.2. Global greenhouse gas emissions

Existing Trends shows annual global GHG emissions in 2050 around 40 percent higher than current levels, consistent with temperatures increasing by around 3°C by the end of the century, and continuing to rise thereafter.

However, ambitious global action to reduce emissions would see global annual emissions fall by 56 percent from 2015 levels by 2050, and by 63 percent by 2050 when these abatement policies are combined with resource efficiency.

The outcomes for the Efficiency Plus scenario are thus consistent with the call by G7 leaders for "a global goal of greenhouse gas emissions reductions … [in] the upper end of the latest IPCC recommendation of 40 to 70% reductions by 2050 compared to 2010" (G7 Summit 2015:12).

Improved resource efficiency alone reduces annual global GHG emissions by 19 percent in 2050 relative to *Existing Trends* (Figure 116).

2.5.3. Global economic performance

Stronger underlying growth in natural resource use in developing and emerging economies results in resource efficiency having larger economic benefits globally than in G7 nations alone.

Resource Efficiency boosts economic growth relative to *Existing Trends*, adding US$10,000 billion (US$1,000 per person) to the value of the Gross World Product (GWP) in 2050. This figure is over US$2,000 billion (US$200 per person) in the Efficiency Plus scenario that both reduces total resource use and puts the world on track to limit global warming to 2°C or lower. These gains are equivalent to boosting GWP by 6.5 percent and 1.5 percent respectively in 2050, relative to *Existing Trends*. This contrasts with the Ambitious Climate scenario, without

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

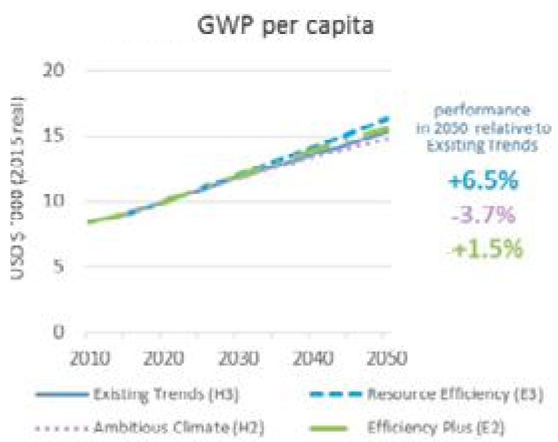
improved resource efficiency, where limiting global warming to 2°C or lower is projected to slow economic growth before 2050, with GWP per capita 3.7 percent lower than *Existing Trends* in 2050 (Figure 117). However, other studies have found that stringent emissions reductions of this kind would boost economic growth after 2050 by avoiding the worst impacts of climate change (Stern, 2008, Stern, 2013, Nordhaus, 2010).

Nevertheless, these economic gains are not distributed uniformly across countries and regions. Efficiency Plus is shown to provide net economic benefits to 17 of 28 regions, accounting for two thirds (66 percent) of global population in 2050, relative to *Existing Trends*. Disadvantaged regions include South America, Russia, Mexico, Brazil, South Africa, Central Europe, Eastern Europe and West Asia, which would see global resource efficiency dampen demand for their resource exports. Fully compensating disadvantaged regions would require around 40 percent of the net gains of high and medium income nations, but would result in a world on track to keeping temperature rise below 2°C, with no region worse off economically than it would be under *Existing Trends*. The same caveats apply to these results as were noted for those related to the G7 countries. They do not fully account for any policy and other costs that may be incurred to achieve the gains in resource efficiency. Governments should make every effort to implement efficient policies of this kind that will minimize these costs.

2.6. Conclusions

Fresh economic modelling of resource efficiency was carried out for this International Resource Panel study using a multimodel framework including a global CGE economic model. An assessment was made of the impacts of reducing GHG emissions, and extending this to analyse the extraction and use of natural resources, accounting for economic incentives and feedbacks. The results, which are subject to the usual uncertainties and assumptions of such

Figure 117: GWP per capita



exercises (as discussed in Part II - Chapter 3), show that there is substantial potential to achieve economically attractive resource efficiency, providing win-win outcomes that reduce environmental pressures while increasing employment and economic growth.

The starting point for the analysis is the projection that, under *Existing Trends*, global natural resource use will increase from 85 to 186 billion tonnes over the 35 years from 2015 to 2050, reflecting a 28 percent increase in population and a 71 percent increase in per capita resource use. Against this backdrop, the modelling suggests that resource efficiency policies and initiatives could reduce global resource extraction by up to 28 percent globally in 2050 relative to *Existing Trends*. When resource efficiency is implemented in combination with ambitious global action on climate change, the modelling finds that the stronger economic growth associated with resource efficiency policies more than offsets the near-term economic costs of ambitious climate action, boosting the value of economic activity in 2050 by 1.5 percent globally and 1.0 percent in G7 countries relative to *Existing Trends*. This package of measures also sees emissions reductions of 63 percent globally and 74 percent in G7 nations by 2050, relative to 2015 levels. This puts the world on track to limit climate change to below 2°C, with stronger economic growth than under *Existing Trends*.

As noted above and in Part II - Chapter 3, the level and mix of economic and environmental benefits achieved in practice will depend on the detail of the policies and approaches implemented, and the extent to which they manage to minimize the costs incurred, which the modelling was not able to take into account. As such, the specific findings should be treated as illustrative of the potential gains rather than as definitive numerical predictions.

2.7. Appendix: Analytical framework used for the modelling

2.7.1. Overview of approach

The analysis uses model-based scenarios to provide insights into the potential for, and benefits of, ambitious improvements in resource efficiency; and the interactions and potential synergies between resource efficiency and more ambitious action to reduce global GHG emissions and the extent of climate change.

The scenario projections are developed using a multimodel framework, linking a global computable general equilibrium (CGE) economic model (GTEM) to two other models: GLOBIOM, providing additional detail on land use and biofuels, and MEFISTO, a stock-flow model providing insights into resource efficiency potential. This builds on an internationally recognized integrated nexus modelling approach used in the Australian National Outlook (Hatfield-Dodds et al., 2015b, Hatfield-Dodds et al., 2015a).

2.7.1.1. Advantages of approach

Advantages of this analytical framework and approach include:

- integrated analysis, accounting for complex interactions across issues, sectors, and regions
- detailed analysis of economic dynamics, including changes in the supply and demand of different types of materials and energy as a result of the policy changes and scenario assumptions
- rich representation of the global economic processes, including results for 28 countries and regions, 21 sectors, and 10 categories of raw materials, and
- quantified projections with multiple indicators of economic and environmental outcomes — including GDP, agricultural output, resource use, energy, and greenhouse gases — allowing detailed assessment of economic costs and benefits of different scenarios for resource use and environmental pressures.

The analysis demonstrates a novel approach to developing projections of national and global natural resource extractions (DE) and natural resource use (DMC). This production-oriented method can be extended through input-output analysis to report on material footprints by region (Schandl et al., 2015), accounting for resources embodied in imports and exports to provide a consumption-based perspective on resource use. This additional analysis has not been implemented at this stage.

Our projections of resource efficiency potential are deliberately conservative, and can be treated as associated economic benefits of greater resource efficiency. Likewise, our cost estimates of reducing GHG emissions are likely to overstate the real economic costs of shifting onto this pathway. This is due to the model's limited ability to predict the real-world innovations and breakthroughs that would be generated by concerted global efforts to reduce GHG emissions to less than half their current level.

At the same time, our modelling does not fully account for costs that may in reality be incurred when implementing resource efficiency policies and practices. Efficient policy approaches can minimize such costs, but if these were to be significant, the economic benefits of implementing the policies would be lower than the results here suggest.

2.7.2. Terms and definitions used

Resource extraction refers to Domestic Extractions (DE) of materials — biomass, fossil fuels, metal ores, and non-metallic minerals — within a nation or group of nations, and is measured in tonnes.

Resource use refers to Domestic Material Consumption (DMC), defined as Domestic Extractions less exports of primary materials plus imports of primary materials, measured in tonnes.

Resource efficiency refers to a reduction in natural resource use, relative to the *Existing Trends* scenario. We find resource efficiency provides economic benefits in the scenarios modelled, but in principle resource efficiency could provide benefits or costs, and be associated with higher or lower rates of economic growth.

Primary materials refers to unprocessed natural resources, corresponding to the output from the mining, minerals, energy commodities, and agriculture sectors.

Basic materials refers to natural resources that have been simply processed (such as making iron and steel from metal ores and energy inputs), corresponding to outputs from simple processing and manufacturing sectors.

Greenhouse gas emissions include all six climate-forcing gases, and are reported in CO_2e.

Economic activity is measured in real 2007 international dollars (equivalent to US$).

Economic growth refers to an increase in the value of real economic activity.

2.7.3. Implementation of scenarios

2.7.3.1. Development of resource-use projections and the Existing Trends scenario

The modelling begins by establishing a plausible *Existing Trends* scenario, which assumes a continuation of the historical relationship between economic activity, population growth, and resource extraction and use. These linkages are modelled at country and regional scale, and reported as aggregates for G7 countries and the world. Resource extraction (DE) and use (DMC) are based on the GTEM model's projected output volume index for 10 sub-categories of resources (as shown in Table 16), which together account for all material flows. These volume indexes are calibrated to base-year data from the UN International Resource Panel (UN Environment, 2016a) for each of the 28 countries or regions, to provide robust projections of physical resource flows to 2050 (see Part IV - Section 2.7.4.1 for more detail).

The *Existing Trends* scenario serves two main purposes in the analysis. First, it establishes a "business-as-usual" outlook for resource extraction and use, in the absence of major shifts or policy changes. Second, it provides a benchmark or reference point for use in assessing the impacts of potential changes of interest; here the introduction of a set of stylized resource efficiency policies, and more ambitious action to reduce GHG emissions. This provides an estimate of the impacts of these changes relative to *Existing Trends*, rather than to a counterfactual scenario with no climate policy action.

The *Existing Trends* scenario assumes a trend reduction in GHG emissions intensity going forward, so that emissions follow the RCP6.0 pathway, rather than the RCP8.5 pathway (or higher) that the world has tracked over recent years. This scenario represents weak or partial implementation of climate policy (rather than the ambitious review cycle agreed in Paris), and allows the modelling to assess the economic and environmental impacts of strong implementation of the Paris Agreement, relative to this benchmark. Near-term economic growth projections are based on IMF projections to 2030.

2.7.3.2. Modelling approach to achieving improved resource efficiency

The modelling and analysis for this project explored a range of approaches to promoting resource efficiency. These involved different mixes of three key elements.

- Innovation that improves resource efficiency, reducing the unit costs of raw and basic materials. The potential for improved resource efficiency is based on literature review and other analysis of current observable potential for cost-neutral improvements in resource efficiency. We assume that these improvements are achieved progressively over the 2020–2040 period, then continue at the same pace to 2050. These reductions in unit costs would tend to increase total natural resource use, all else being equal (often referred to as the "rebound effect"), and to boost economic growth.
- A resource extraction tax (applied to virgin raw materials) that changes relative prices, thereby reducing resource demand and improving resource efficiency. The modelling assumes that the revenue raised is returned as a lump sum transfer to households in the country of extraction, rather than being used to reduce other taxes (due to the complexity of modelling the tax arrangements of each country or regional grouping). Therefore it does not result in a reduction in tax-related dead weight losses (referred to as a potential "double dividend" from environmental tax reform). As a result, the tax reduces natural resource use and slows economic growth. We find that resource demand is highly inelastic, with a 25 percent increase in price resulting in a 6 percent reduction in quantity demanded. This reflects limited substitutes for raw materials and a lack of endogenous innovation mechanisms in the model.
- Regulations and new information, reducing natural resource demand by reducing the amount of basic materials required to meet a given level of human wants and needs (such as for food, shelter, and mobility). This reduces resource use and boosts economic growth, in part by promoting additional investment.

The Resource Efficiency and Efficiency Plus scenarios adopt a middle ground combination of these elements, the individual and combined impacts of which are shown in Table 15 below. We find more detailed analysis is required to identify the best combinations of practical policy

Table 15: Individual and combined impacts of policy elements on resource extraction, investment and economic activity

	Resource extraction (DE)	Quantity, non-fossil resources	Price, non-fossil resources	Investment	Economic activity (GWP)
	Deviation from Existing Trends				
Innovation	-1.3%	-1.5%	-0.9%	+4.6%	+8.8%
Resource Extraction Tax	-8.3%	-5.9%	+25.9%	-5.0%	-4.2%
Information and regulations	-8.4%	-8.7%	-11.7%	+7.6%	+6.2%
Combined effect (Resource Efficiency Scenario)	-17.6%	-16.1	+10.7%	+8.1%	+6.2%

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

and business options for improving resource efficiency, particularly through innovations that reduce natural resource use while better meeting human needs.

2.7.3.3. Modelling approach to achieving greenhouse gas reductions

The *Existing Trends* scenario assumes that each country or region achieves relevant Paris pledges (INDCs) to reduce emissions, to 2025 or 2030, and then tracks the RCP6.0 global cumulative emissions pathway. This is implemented through country- or region-specific emissions targets reflecting relevant commitments, and then a uniform global carbon price calibrated to achieve the required global emissions. The same approach is used for the *Climate Only* scenario, but calibrated to achieve RCP2.6. The resulting carbon price trajectory is also applied in the *Efficiency Plus* scenario. The modelling does not implement any form of tradable emissions entitlements. Although such trading will not affect the total global impacts of emissions reductions, its distribution of impacts does differ from scenarios that assume a different approach to burden- and benefit-sharing.

2.7.3.4. Overview of key results

Table 16 below provides an overview of changes in global material flows (by detailed subcategories), population, and economic activity from 2015 to 2050.

2.7.3.5. Comparisons to other studies

Our projected reductions in natural resource use are smaller than those implied by other projections for specific sectors, although direct comparisons are difficult. We judge this to be for two major reasons. First, in contrast to studies that focus on potential reductions in resource intensity (Schandl et al., 2015), the modelling for this study finds that economic dynamics (particularly the flow-on effects of lower unit resource costs, commonly referred to as the "rebound effect") significantly reduce the extent of net resource efficiency gains. Second, we have not been able to develop robust economy-wide estimates of the implications of recycling, refurbishment and remanufacturing on the demand for raw materials. This prohibits an economy-wide "circular economy" approach from being modelled (EMF, 2015, Böhringer and Rutherford, 2015).

2.7.4. Modelling framework

2.7.4.1. Component models and key linkages

We use a novel global multi-model framework to develop projections of natural resource use to 2050 under Existing Trends and three policy scenarios, underpinned by detailed analysis of economic dynamics and incentive effects. These include changes in the supply and demand of different types of materials and energy under Existing Trends and three scenario assumptions. The material flow accounts use the input-output structure of the global economic model to project the physical volume of all material flows, divided into 10 subcategories, in addition to energy (by source and end use), and greenhouse gases (see Table 17). The modelling uses GTEM, an economy-wide computable general equilibrium (CGE) model with 28 regions and 21 industry sectors (see below), with an established track record in the analysis of climate policy (Garnaut, 2008), food security and agricultural productivity (Scealy et al., 2012, Hanslow et al., 2014). We also link GTEM to GLOBIOM to provide a physically grounded perspective and additional detail on land use, agricultural production, and biomass supply, GHG emissions from land use and land-use change, and competition between alternative land sector outputs.

The analysis demonstrates a novel whole-of-economy approach to developing projections of natural resource extraction, trade, and domestic use. We repurpose an established CGE model to provide a physical volume index for 10 subcategories of material flows, and apply these to base-year data from the International Resource Panel (UN Environment, 2016a) to

Table 16: Global material flows (by category), population, and economic activity, 2015 and 2050 for four scenarios

	2015	2050			
		Existing Trends	Resource Efficiency	Climate Only	Efficiency Plus
POPULATION					
Population, billion people	7.3	9.3	9.3	9.3	9.3
Change from 2015		27.8%	27.8%	27.8%	27.8%
ECONOMIC ACTIVITY					
World Gross Product, US$ trillion ($2015 real)	76.2	164.7	175.4	158.6	167.1
Change from 2015		116.0%	130.0%	108.1%	119.2%
MATERIAL FLOWS, billion tonnes					
RESOURCE USE (DMC)					
Domestic Material Consumption (a)	85.0	186.1	153.8	162.9	134.5
Change from 2015		118.8%	80.8%	91.6%	58.2%
RESOURCE EXTRACTION (DE)					
Biomass					
Crops	12.4	21.7	17.6	19.5	15.9
Livestock and other animals	6.3	11.8	9.4	10.2	8.0
Fishing	0.2	0.4	0.3	0.3	0.3
Forestry	3.1	7.1	4.1	7.4	4.3
Fossil fuels					
Coal	7.8	11.5	9.1	4.9	3.6
Oil	4.3	6.6	4.2	5.0	3.3
Natural gas	2.3	3.9	2.4	2.0	1.3
Metal ores					
Ferrous metal ores	2.5	4.7	2.5	4.7	2.5
Non-ferrous metal ores	5.7	11.5	8.8	11.9	9.4
Non-metallic minerals					
Non-metallic minerals	39.0	104.5	92.9	95.0	83.5
Total (a)	83.7	183.7	151.3	160.9	132.1
Change from 2015		119.5%	80.8%	92.3%	57.8%

Notes: (a) Total resource use and resource extraction may differ slightly in a specific year due to differences in the timing of extraction and use associated with international trade.

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

generate projections of domestic extraction (DE), physical trade balance (PTB), and domestic material consumption (DMC) to 2050. This draws on the input-output structure of the model, as shown in Table 17. Material flow data and indicators are defined and measured following the methodological guidelines provided by the European Statistical Office (Eurostat, 2013) and the OECD, and are consistent with the international standards for national and global material flow accounting (Fischer-Kowalski et al., 2011). This production-oriented approach can be extended through input-output analysis to report on material footprints by region (Schandl et al., 2015), accounting for flows of natural resources through national and international supply chains to provide a consumption-based perspective on natural resource use. This additional analysis has not been implemented at this stage.

2.7.4.2. Resource extraction and use categories

Projections of resources extractions (DE) and use (DMC) are developed using the input-output relationships of key primary production sectors, as set out below in Table 17.

2.7.4.3. TEM regions and sectors

The version of GTEM used for this project has 28 countries or world regions, as shown below in Table 18, including each G7 nation, the BRIC nations, and most G20 nations.

The model also has 22 sectors, with particular attention to agriculture and other materials and energy intensive sectors, as shown in Table 19.

Table 17: Material flows, energy, and greenhouse gas emissions in relation to GTEM sectors

	PRODUCING SECTORS	RECEIVING SECTORS
MATERIAL FLOWS		
Fossil Fuels	Coal	All
	Oil	All
	Gas extraction	All
Metal ores	Other mining	Iron and steel
	Other mining	Non-ferrous metals
Minerals	Other mining	All other (NMM)
Biomass	Crops (incl. biofuels)	All
	Livestock	All
	Other animals and fishing	All
	Forestry	All
ENERGY AND EMISSIONS		
Primary energy	Composite from coal, oil, gas and electricity	All
GHG emissions (CO_2e)	Composite from all sectors other than manufacturing, processed food and services	Not applicable

Table 18: GTEM countries and regions

28 countries and regions	Code	Group	Countries and regions included	Geographic grouping
Australia	AUS	Other OCED	Australia	Asia-Pacific
China	CHN	BRICS	China	
East Asia and Oceania	EAO	ROW	Cambodia, Hong Kong, Lao PDR, Malaysia, Mongolia, Philippines, Singapore, Taiwan, Thailand, Vietnam, Rest of East Asia, Rest of Oceania, Rest of South-East Asia	
India	IND	BRICS	India	
Indonesia	IDN	ROW	Indonesia	
Japan	JPN	Other OCED	Japan	
Korea	KOR	Other OCED	Korea	
New Zealand	NZL	Other OCED	New Zealand	
South Asia	SAS	ROW	Bangladesh, Nepal, Pakistan, Sri Lanka, Rest of South Asia	
Canada	CAN	Other OCED	Canada	North America
Mexico	MEX	Other OCED	Mexico	
United States	USA	G7	USA	
Brazil	BRA	BRICS	Brazil	South and Central America
Central America	CAM	ROW	Belize, Bermuda, Caribbean, Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua, Panama	
Northern South America	NSA	ROW	Bolivia, Colombia, Ecuador, Paraguay, Peru, Venezuela, Rest of South America	
Southern South America	SSA	ROW	Argentina, Chile, Uruguay	

Central Europe	CEU	ROW	Bulgaria, Croatia, Cyprus, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Romania, Slovakia, Slovenia, Turkey	Europe
France	FRA	G7	France	
Germany	DEU	G7	Germany	
Italy	ITA	G7	Italy	
United Kingdom	GBR	G7	United Kingdom	
Western Europe (ex-G7)	WEU	Other OCED	Austria, Belgium, Denmark, Finland, Greece, Iceland, Ireland, Liechtenstein, Luxembourg, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland	
E. Europe & W. Asia	EEW	ROW	Albania, Armenia, Azerbaijan, Bahrain, Belarus, Georgia, Iran, Iraq, Israel, Jordan, Kazakhstan, Kyrgyzstan, Lebanon, Moldova, Oman, Palestinian Qatar, Syria, Saudi Arabia, UAE, Ukraine, Yemen, Rest of Former Soviet Union (FSU), Rest of Western Asia	West Asia
Russia	RUS	BRICS	Russian Federation	
Central Africa	CAF	ROW	Cameroon, Kenya, Nigeria, Tanzania, Uganda, Rest of Eastern Africa, Other Central Africa	Africa
North and West Africa	NWA	ROW	Algeria, Côte D'Ivoire, Egypt, Ethiopia, Ghana, Kuwait, Libya, Morocco, Tunisia, Rest of North Africa, Rest of Western Africa	
Other Africa	OAF	ROW	Botswana, Lesotho/Swaziland, Madagascar, Malawi, Mauritius, Mozambique, Namibia, Senegal, Zambia, Zimbabwe	
South Africa	SAF	BRICS	South Africa	

Table 19: GTEM sectors

Sector groups	Sectors
Mining and energy commodities	Coal
	Oil
	Gas extraction
	Other mining (OMN)
Agriculture	Crops
	Livestock (cattle, sheep, dairy)
	Other animals
	Fishing
	Forestry
Heavy industry	Non-metallic minerals (NMM)
	Petroleum & coke products
	Electricity
	Iron & steel
	Non-ferrous metals
	Chemicals, rubber, plastics
Manufacturing	Manufacturing
	Processed food
Transport	Land and other transport
	Water transport
	Air transport
Other services	Construction
	Services

2.7.5. Modelling limitations

The modelling has a number of limitations that are relevant to interpreting the results.

Scenario modelling provides insights into impacts of different courses of action by comparing the results of different scenarios. Scenarios represent plausible and internally coherent future pathways, and are not predictions of the future. The analysis for this project assumes smooth future pathways, and does not account for variability and instability such as “booms and busts” in global economic markets; weather- and climate-related events; or wars, social unrest and geopolitical disturbances. The modelling framework reflects incremental innovation and improvements in technology as changes in the input-output ratios of each sector. However, it does not include

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

endogenous mechanisms representing the possibility of innovation breakthroughs, such as the development of new types of goods and services, or step-changes in production processes and efficiencies.

The modelling provides projections of resource extraction and use by using production volume indexes of relevant sectors to weight base-year data on resource use and domestic material extractions. This provides an internally coherent framework for developing projections of resource demand and supply, accounting for interactions along the supply chain and across different sectors. The approach is novel, however, and meets a previously unmet analytical need. This implies that although the projections for the *Existing Trends* scenario are calibrated to historical experience, there is not a well-established literature or set of other global projections that can be used as a point of comparison in considering our results.

Our projections of resource efficiency potential are deliberately conservative, and can be treated as a reasonable minimum estimate of the potential to achieve reductions in resource use, and the associated economic benefits of greater resource efficiency. Likewise, our estimates of reducing GHG emissions are likely to overstate the real economic costs of shifting onto this pathway. This is due to the models' limited ability to predict the real-world innovations and breakthroughs that would be generated by concerted global efforts to reduce GHG emissions to less than half their current level.

The framework accounts for the economic costs of reducing GHG emissions, but to simplify the analysis and improve transparency, the analysis does not include climate feedbacks or the benefits of avoided GHG emissions. Nor does the analysis account for potential impacts of climate change on resource extraction and use, such as improved access to some Arctic resources (due to reductions in sea ice) or reduced crops and livestock output (biomass flows) associated with drought or other extreme events. In practice, climate change is expected to result in more frequent — and in some cases more severe — extreme weather events, including droughts, heatwaves, storms and floods, which will have significant impacts in some locations and sectors in some years. Aggregate global economic impacts are highly uncertain, however, although the literature in this area is improving rapidly (OECD, 2015a). Detailed modelling of climate impacts, and thus the global benefits of reduced global GHG emissions, was beyond the scope of this analysis. The analysis will thus tend to understate the benefits of stronger action to reduce emissions.

As noted in earlier sections, the modelling has not fully accounted for costs related to either resource efficiency policies or the innovation that will undoubtedly be required to achieve the increases in resource efficiency assumed by the modelling. If significant, such costs may, in practice, reduce the economic benefits of such increases.

The economic model has been calibrated to analyse GHG reduction polices and has extended technology bundles for electricity production, transport and land use. Their use in modelling resource efficiency is novel, and similar detailed technology bundles for built infrastructure (residential and commercial building, transport and communication infrastructure) are being developed, but are not fully implemented in this study. Enhancing these technology details would enable more in-depth analysis of market and policy-driven innovations that could have significant impacts on demand for natural resources and the potential to decouple the quantity of resource use from the services derived from that use.

PART V: CONCLUSIONS

1. CONCLUSIONS

This report is the International Resource Panel's response to the G7 invitation *"to prepare a synthesis report highlighting the most promising potentials and solutions for resource efficiency in industrialized countries as well as in emerging market economies and developing countries."* **The report and its Summary for Policymakers provide compelling evidence that an increase in the resource efficiency ambitions of policymakers in all countries is both necessary and possible.**

1.1. The imperative and opportunity of resource efficiency

The imperative for increased resource efficiency arises from the pressure that population and economic growth, combined with increasingly unsustainable patterns of production and consumption, are putting on natural resources and the environment. These are manifest in the extreme volatility of resource prices, including for food — the most basic of human needs. Serious concerns have arisen about the adequacy and availability of key resources, including water and certain critical materials. Finally, there are far too many examples of systematic environmental harm, owing to pollution, resource degradation and biodiversity loss. These pressures amount to threats which, if not addressed, could overwhelm attempts at human development. Notably, they could make it much more expensive, or even impossible, for the global community to achieve either the SDGs or the climate targets enshrined in the Paris Agreement.

Policymakers must address and avert the threats as far as possible, by making a systematic effort to achieve a substantial increase in their economies' resource efficiency. This would entail an increase in the technical efficiency with which economic processes turn material and energy inputs into useful outputs, a reduction in associated environmental impacts, and an increase in the value that economic processes add to each unit of material and energy input. Increasing resource efficiency therefore means increasing both technical efficiency and resource productivity, and reducing environmental intensity.

The opportunities offered by increased resource efficiency arise from its potential to result in higher economic growth and employment. This potential is apparent in modelling studies, even when resource-efficient scenarios are compared with projected development paths that fail to factor in the costs of resource bottlenecks, pollution and climate change, which improved resource efficiency can help mitigate. The benefits from increased resource efficiency would therefore be even greater if these avoided costs of supply bottlenecks, pollution and climate change were taken into account.

Markets, however, will not achieve these higher levels of resource efficiency unaided. The studies that show higher growth and employment from greater resource efficiency suggest that this is driven by a number of different mechanisms. These include: higher rates and different directions of innovation and technical change than markets can achieve by themselves; higher investments in resource-efficient infrastructure and products; intelligent and targeted regulation; and environmental tax reform that adjusts the balance between the costs of labour and materials, thereby increasing the economic return to resource-efficient products and processes. Environmental tax reform is especially important as a means of avoiding the rebound effect, whereby increased economic activity arising from increased resource efficiency reduces the benefits from lower resource use and pollution that would otherwise have been achieved.

The financial and employment benefits from increased resource efficiency are much enhanced by the non-financial benefits that are just as important for human well-being. These benefits are derived from resource security, reduced pollution, improved health, enhanced environmental quality, greater climate stability and lower loss of biodiversity. Moreover, resource efficiency provides opportunities for improving the social allocation of resources. Reducing the stress on the quantity and quality of resources will enable the disadvantaged and the poor to access the resources they need more easily. The resource efficiency agenda therefore offers the potential to reduce inequalities and poverty through more secure access to resources for those who currently have least access.

Pursued through well-informed and appropriate public policy, increased resource efficiency can therefore deliver multiple benefits across all the dimensions — economic, social and environmental — of sustainable development. Moreover, increased resource efficiency is indispensable in helping countries meet their aspirations as enshrined in the SDGs and the Paris Agreement on Climate Change.

1.2. Good practices for resource efficiency

There is no magic formula to increase resource efficiency. The necessary measures — technical, economic and policy-related — vary from sector to sector, from resource to resource, and from country to country.

The evidence in this report has provided many examples of resource efficiency solutions, showing how greater efficiency can be achieved in the management of resources — energy, water, materials, the biomass deriving from land and the oceans and, indeed, the land itself. The measures differ in detail, dealing as they do with different resources and different economic sectors and processes, but some common messages are highlighted here.

Most importantly, **there are significant barriers to achieving the required increases in resource efficiency**. Such increases will not emerge through the operation of market forces alone. Therefore, different economic actors, in collaboration with policymakers, must do things differently for rates of resource efficiency to increase. For this to happen, there must be strong incentives for more resource-efficient practices that are currently lacking. This report therefore ends with a number of suggestions emerging from the good-practice examples that have been reviewed, through which higher resource efficiency has been attained. In addition, some of the examples presented earlier in the report are briefly highlighted to show how these suggestions have already been successfully implemented in some cases.

First, there is the issue of short-term versus long-term returns. For firms in industries with volatile prices requiring short payback times, or for other actors with limited capital availability, some investments in resource efficiency are not possible. This may also be an issue in developing economies, which are expanding rapidly but lack the resources to make strategic resource-efficient interventions, for example in urban areas. This issue can be addressed in a number of ways, such as providing "patient" capital or development funding that focuses on improving long-term productivity and maintaining/restoring land quality, and not on generating quick returns from high inputs. Supporting businesses in price-volatile sectors, or providing a clear outlook on future policy trajectories across sectors, can help businesses justify long-term investments. Financial support is also needed to enable developing countries and cities to make long-term resource-efficient infrastructure planning decisions.

Support for businesses in volatile sectors

The Rathkerewwa Desiccated Coconut Mill in Sri Lanka was assisted under UNIDO's RECP programme to identify relatively simple material efficiency measures, concerning the handling of the produce, the reuse of waste by-products for energy, and water-saving. The measures required an investment of less than US$5,000 but provided combined savings of US$200,000 (see Part III - Section 4.3).

Clear outlook on future policy trajectories

In Japan, the "Top Runner" energy efficiency scheme has succeeded in dramatically driving up efficiency standards by clearly setting out, in advance, the required standard of the future year. This provides companies with the confidence and incentive to invest in technological improvements. Over the programme's first 12 years, efficiency improvements in different product groups have ranged from 16 percent to 80 percent in the target year (see Part III - Section 3.4.1).

Long-term resource

The Indian city of Ahmedabad chose to undertake its transportation planning alongside its broader Development Plan, and to give the resulting Integrated Mobility Plan a time-horizon of 20 years. This long-term integrated plan was therefore able to consider mobility in the context of its other planning strategies, especially high-density, mixed-use urban infrastructure, resulting in numerous co-benefits. Local public transit systems were connected to mass transit systems at hub points, and dedicated walking and cycling lanes were also included alongside the bus rapid transit corridors (see Part III - Section 5.3.4).

Second, resource efficiency and economic efficiency are not always linked. Despite the overall evidence of the potential long-term economic benefits of resource efficiency at the societal level, resource efficiency and economic efficiency often do not coincide for individual firms and actors. For example, the trade-off between low material costs and high labour costs can make it cheaper to waste materials than invest in the labour required to avoid wasting them. Again, there are numerous possible ways to strengthen the link between resource efficiency and economic efficiency, generally tending towards taxing labour less and resources and pollution more. This can be accomplished by pricing externalities and using taxation to stimulate investment in resource-efficient alternatives; introducing resource extraction taxes to increase the price of materials and thereby the economic incentive to use them efficiently; using dynamic taxes to buffer price fluctuations, thereby reducing volatility and future uncertainty; and/or creating other incentives for actors to favour paying for labour to save materials, rather than for materials to save labour.

Trade-off between low material costs and high labour costs

In commercial building projects, materials are often over-specified beyond the needs of the safety standards. This inefficient use of materials may be driven by the fact that the added cost of the materials is lower than the increased cost of engineering design time that would be required to achieve a design that met the safety standards with an optimal material mass. In such situations, optimizing material efficiency is not consistent with optimizing economic efficiency. Computerized production systems and technologies may reduce the cost penalties of component optimization, and product certification that proclaims embodied energy efficiency of buildings, cars and other products may help stimulate a market-pull for such materially efficient design innovations (see Part III - Section 2.2.3).

Incentivizing investment in resource-efficient waste and resource management

The UK Landfill Tax was introduced in 1996, when the household waste recycling rate was just 7 percent. From 1996 to 2015, the Landfill Tax rate increased from GBP£7 to GBP£82. The 2014 household waste recycling rate was 44 percent (see Part III - Section 2.4.3).

Third, ongoing urbanization processes must become more resource-efficient. Resource efficiency needs to be a guiding principle for the towns and cities springing up and being extended in many countries around the world. This applies to buildings, transport systems and infrastructure to enable the coordinated management of materials, water and energy, making full use of modern information and communication technologies. Such infrastructure may require public as well as private investment.

Resource-efficient urbanization

Vauban, Germany, is an eco-city development with sustainability embedded into the design of the project itself, with all of the housing designed to a high efficiency standard. The area is designed to enable sustainable transport, with all homes within easy walking distance of a tram stop. The district has also been laid out to actively encourage walking and cycling and discourage car use. Thus, transport is primarily on foot or by bicycle (see Part III - Section 3.4.5).

Fourth, logistics and supply chains can be improved. The reuse and recycling of resources require used materials to flow in the opposite direction to product supply chains. This requires various actors to adopt a coordinated approach to the planning of resource management, and to the logistics of material and product supply and return. Considering these areas in an integrated way, for example through industrial symbiosis, can foster synergies and benefits.

Industrial symbiosis eco-towns

Kawasaki Eco-Town in Japan aims to recycle the city's waste for use as raw materials for the cement-, iron- and steel-works located in the city, for example by recycling plastic as a reductant for blast furnaces, for concrete formwork and for ammonia production. The town is also active in paper recycling and PET-to-PET plastic recycling. As well as reducing material waste, the industrial symbiosis strategy in Kawasaki is estimated to have reduced life-cycle carbon emissions by 13.77 percent, mainly from iron, steel, cement and paper manufacture (see Part III - Section 2.4.3).

Supply-chain coordination, with consumer involvement

An estimated GBP£1 billion worth of electrical and electronic goods are sitting unused in UK homes. The UK retailer Argos has developed an appliance trade-in scheme in its UK stores, allowing consumers to trade in unwanted electrical goods for an Argos store voucher. The item is then sent to an IT asset management company (ITAM) for reuse or recycling. The scheme provides consumers with an incentive to return unwanted material goods, as well as convenient locations to do so. The store and ITAM can also benefit from the value of the reclaimed materials (see Part III - Section 2.4.1.2).

Industrial symbiosis networking

Over 2005–2010, the UK's National Industrial Symbiosis Programme (NISP) received GBP£28 million in public funding, which it used to divert 7 mt materials from landfill by enabling them to be reused or recycled, reduced CO_2 emissions by 6 mt, saved 9.7 mt virgin materials and 9.6 mt water, and reduced hazardous waste by 0.36 mt. It also increased business sales by GBP£176 million, reduced business costs by GBP£156 million, leveraged GBP£131 million in private investment, and saved or created a total of 8,700 jobs. This extra economic activity meant that the Treasury received in taxes more than three times its original GBP£28 million investment (see Part III - Section 2.4.3).

Fifth, regulations that militate against resource efficiency should be changed. For example, rules set up to manage a linear material management chain may prevent material classified as waste from re-entering the supply chain. This suggests that regulations that govern materials, water and energy flows, while continuing to safeguard human health and the environment, should be revised to enable more circular resource flows. This could include revisiting definitions and provisions for waste management, and removing counter-productive subsidies.

The market importance of definitions, standards and transparency

The Action Plan of the European Commission's Circular Economy Strategy seeks to clarify a number of issues that are crucial to the growth and proper functioning of the markets for secondary raw materials. These include distinguishing such materials from waste, setting quality standards for them and clarifying extended producer responsibility (EPR) schemes for their management. When effectively implemented, EPR schemes can greatly increase the quantity of materials recovered for recycling: schemes in Sofia in Bulgaria increased the recycling of WEEE by over 150 percent over four years, while buy-back campaigns in Romania have led to 80–90 percent recycling of WEEE, equivalent to 30 percent of waste sales in Romania (see Part III - Section 2.4.1.6).

Sixth, the issue of possible "losers" from resource efficiency needs to be addressed. In some industries, reduced material extraction will translate as reduced revenues and job losses. In this context, it is important that transitional issues are properly addressed and appropriate compensation for "losers" considered. However, it should be noted that resource efficiency has the potential to create jobs in other areas. Therefore, rather than resisting resource efficiency or supporting resource-inefficient activities (which may already be in decline), it may be preferable to set up programmes to transfer redundant workers to, and retrain them for, resource-efficient sectors and activities.

Addressing transitional issues from restructuring for resource efficiency

Examples from China and Norway show how necessary restructuring to enhance resource efficiency can be carried out in ways that mitigate social impacts and provide the basis for new industries. China's concern to reduce deforestation resulted in about 1 million people being helped to redeploy into new business areas, and Norway rescued its fish stocks from crisis by greatly reducing its fishing fleet, retraining workers to find alternative employment in the short term, and setting up longer-term programmes of education and investment in alternative business activities (see Part II - Section 3.1).

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

Seventh, a whole-system approach needs to be applied, bearing in mind that there may be points after which recycling is no longer energy-efficient. There may also be complexities and unintended consequences, in terms of other environmental impacts of resource-efficient initiatives, and from the interactions between different resources.

To guard against such situations, a whole-system approach is needed to assess resource use and the impacts of products on a life-cycle and consumption-production basis, with the insights used to inform and amend policy where necessary.

Understanding limits to recycling

There are limits to recycling: for example, as it is not yet possible to precisely control alloy composition when refining molten scrap, recycled steel is not used for some higher grade applications. On the other hand, often aluminium can be recycled repeatedly without loss of properties, if non-contaminated (see Part III - Section 2.4.1.2).

Life-cycle analysis is a necessary tool to determine when recycling is beneficial from an environmental and resource point of view. For example, for glass, the energy needed for recycling is similar to the energy required for virgin production; this may be an important factor to consider when assessing the environmental benefits of recycling. Limits to recycling arise both from fundamental principles such as the second law of thermodynamics, from technological constraints, and also from human failure to understand, design and operate recycling systems effectively (see Part III - Section 2.4.2).

Eighth, national and international targets for resource efficiency should be adopted and progress towards them monitored. This would give policymakers and businesses a greater incentive to prioritize resource efficiency. To some extent, this situation will be improved if it is realized that resource efficiency is in fact essential to attaining numerous SDG targets. However, it should also be recognized that a specific resource efficiency target, or a small set of targets covering key resources such as materials, water, land and carbon, could be effective in driving performance, and establishing a common view of the future between government, industry and society. A monitoring process to assess the resource use and resource efficiency of different countries, with harmonized metrics and the results published at regular intervals, could give resource efficiency a higher profile and lead to greater ambition to increase it, in the same way as currently occurs for GDP growth.

Carbon targets

In Germany, a key long-term overarching framework is the Energy Concept, unveiled in 2010, which “provides the long-term policy basis” to achieve the goal of energy system transition. A 2012 amendment to the German Renewable Energy Sources Act explicitly enshrines the renewable electricity targets of the Energy Concept in law. Thus, the penetration of renewables in the German supply must be at least 35 percent in 2020, 50 percent in 2030, 65 percent in 2040 and 80 percent in 2050.

In the UK, the target that GHG emissions should be 80 percent below 1990 levels by 2050 is enshrined in the Climate Change Act 2008. To manage the intervening periods, the Government must set five-year successive “carbon budgets”, which plot the short and medium pathway towards the 2050 target. The Government is advised and monitored by an independent body, the Committee on Climate Change (see Part III - Section 6.1).

Setting national resource efficiency targets

As Part of its Sound Material-Cycle Society policy, Japan adopted targets for 2020 for resource productivity, the recycling (cyclical use) rate and final disposal to landfill. These targets have already been met, or on the basis of current trends seem very likely to be met. However, resource productivity indicators can give different impressions depending on whether they are on a DMI or RME basis: from 2000 to 2012, in Japan the increase in DMI-based productivity was 54 percent, while on an RME basis it was only 30 percent (see Part IV - Section 1.1.4).

Given its links to the attainment of the SDGs and the aspirations for GHG emission reductions in the Paris Agreement, improved global resource efficiency ranks among the top priorities for securing sustainable development now and in the future. The new G7 Alliance for Resource Efficiency is well placed to take a lead in this area, showing what is possible in some of the world’s wealthiest and most dynamic economies and taking the initiative to enable and encourage the emerging and developing world to adopt a more resource-efficient development pathway, to the benefit of the whole global community. What is required is a process of continuous exchange, partnership and working cooperatively at all levels, involving mutual support, learning and capacity-building, that gives practical expression and effect to the spirit and common aspirations that led to the agreement of the SDGs.

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

References

350.org. (2015). Divestment Commitments Overview. Available from: http://gofossilfree.org/commitments/

Accor. (2013). *Sustainable Development: Reinventing Hotels Sustainably*. Available from: http://www.accor.com/fileadmin/user_upload/Contenus_Accor/Developpement_Durable/pdf/en_ra2013_rse.pdf

ActionAid. (2011). Smallholder-led Sustainable Agriculture. An ActionAid International Briefing.

Addams, L., Boccaletti, G., Kerlin, M., & Stuchtey, M. (2009). *Charting our water future. Economic frameworks to inform decision-making*. 2030 Water Resources Group, McKinsey and Company.

AfDB. (2014). *Transitioning towards Green Growth: A Framework for the African Development Bank*. African Development Bank.

Agarwal, A., Nanda, B., & Maity, D. (2014). Experimental investigation on chemically treated bamboo reinforced concrete beams and columns. *Construction and Building Materials, 71*, pp. 610-617.

Aggarwal, S., & Elbow, K. (2006). *Lessons Learned: Property Rights and Natural Resource Management.* USAID.

Agnolucci, P., Biedka, M., Coburn, J., Downey de Oliveira, C., Drummond, P., Fawcett, T., ... Ekins, p. (2015). *SPLiCE Phase 1. Significant evidence gaps on the environmental, social and economic impacts of energy system components. Outputs from SPLiCE Phase 1. Report for Defra.* Ricardo-AEA.

Agrawal, p. (2008). *Designing an effective leakage reduction and management program.* Washington, D.C.: World Bank.

Ahmed, S., & Potter, D. M. (2006). *NGOs in International Politics: Kumarian Press.*

Ali, M. H., & Ali, M. H. (2008). Increasing water productivity in crop production—A synthesis. *Agricultural Water Management*, 95(11), pp. 1201-1213.

Allan, G., Gilmartin, M., McGregor, P., Swales, K., & Turner, K. (2009). Modelling the Economy-Wide Rebound Effect. In H. Herring & S. Sorrell (Eds.), *Energy Efficiency and Sustainable Consumption: the Rebound Effect* (pp. 69-98). Basingstoke/New York: Palgrave Macmillan.

Allwood, J. (2014). Squaring the circular economy: the role of recycling within a hierarchy of material management strategies *Handbook of Recycling.* Amsterdam: Elsevier.

Allwood, J., Ashby, M., Gutowski, T., & Worrell, E. (2011). Material efficiency: a white paper. *Resources Conservation and Recycling*, 55, 362-381.

Altieri, M. (2002). Agroecological Principles for Sustainable Agriculture. In N. Uphoff (Ed.), Agroecological Innovations: *Increasing Food Production with Participatory Development.* London: Earthscan.

Altieri, M. A., Funes-Monzote, F. R., & Petersen, p. (2011). Agroecologically efficient agricultural systems for smallholder farmers: contributions to food sovereignty. *Agronomy for Sustainable Development*, 32(1), 1-13.

AMEC, & BioIS. (2013). *The opportunities to business of improving resource efficiency.* Final Report to the European Commission. Available from: http://ec.europa.eu/environment/enveco/resource_efficiency/pdf/report_opportunities.pdf

Amin, S. H., Zhang, G., & Akhtar, p. (2017). Effects of uncertainty on a tire closed-loop supply chain network. *Expert Systems with Applications*, 73, 82-91.

Anderson, J. M., Kalra, N., Stanley, K. D., Sorensen, P., Samaras, C., & Oluwatola, O. A. (2016). *Autonomous Vehicle Technology: A Guide for Policymakers.* Available from: http://www.rand.org/pubs/research_reports/RR443-2.html

Andrew, M., & Yali, p. (2012). *The Rise of the Middle Class in Asian Emerging Markets.* KPMG.

Andrews-Speed, P., Bleischwitz, R., Boersma, T., Johnson, C., Kemp, G., & VanDeveer, S. D. (2012). *The Global Resource Nexus: the struggles for land, energy, food, water and minerals.* Available from: http://www.transatlanticacademy.org/sites/default/files/publications/TA%202012%20report_web_version.pdf

Angel, S. (2012). *Planet of Cities.* Hollis, New Hampshire: Puritan Press.

Anseeuw, W., Alden Wily, L., Cotula, L., & Taylor, M. (2012). *Land Rights and the Rush for Land: Findings of the Global Commercial Pressures on Land Research Project.* Rome: International Land Coalition.

APCC. (2007). *Australian and New Zealand Government Framework for Sustainable Procurement.* Available from: http://www.apcc.gov.au/ALLAPCC/APCC%20PUB_ANZ%20Government%20Framework%20for%20Sustainable%20Procurement%20-%20Sept%202007.pdf

Arena, U., Mastellone, M. L., & Perugini, F. (2003). Life cycle assessment of a plastic packaging recycling system. *The International Journal of Life Cycle Assessment*, 8(2), 92-98.

Argonne National Laboratory. (2014). GREET mini-tool and sample results from GREET 1 2014. Available from: https://greet.es.anl.gov/results

Arvesen, A., Nes, R., Huertas Hernando, D., & Hertwich, E. (2014). Life cycle assessment of an offshore grid interconnecting wind farms and customers across the North Sea. *The International Journal of Life Cycle Assessment*, 19(4), 826-837.

Arvesen, A., Zhongying, W., Jingting, Y., Mingliang, L., & Hertwich, E. G. (2015). Wind power. In E. G. Hertwich (Ed.), *Green Energy Choices: The Benefits, Risks and Trade-offs of Low-Carbon Technologies for Electricity Production.* Nairobi, Kenya: UN Environment.

ADB (Asian Development Bank). (2008). *Toward Resource-Efficiency Economies in Asia and the Pacific: Reduce, Re-use, Recycle.* Asian Development Bank.

ADB (Asian Development Bank). (2015). *Energy efficiency developments and potential energy savings in the Greater Mekong Subregion.* Mandaluyong City, Philippines: Asian Development Bank

Assefa, G. (n.d.). *Leapfrogging Possibilities for Sustainable Consumption and Production in Africa: an Overview.* Berlin: Federal Ministry for the Environment, Nature Conservation and Nuclear Safety.

Bache, I., & Flinders, M. (Eds.). (2004). *Multilevel Governance*. Oxford: Oxford University Press.

Bahn-Walkowiak, B., & Steger, S. (2015). Resource Targets in Europe and Worldwide: An Overview. *Resources*, 4(3), 597-620.

Bakken, T. H., Sundt, H., Ruud, A., & Harby, A. (2012). Development of Small Versus Large Hydropower in Norway– Comparison of Environmental Impacts. *Energy Procedia*, 20, 185-199.

Ballantyne, R., & Packer, J. (Eds.). (2013). *International Handbook on Ecotourism*. Cheltenham: Edward Elgar.

Bankes, N. (2010). International Human Rights Law and Natural Resources Projects Within the Traditional Territories of Indigenous Peoples. *Alberta Law Review*, 47(2), 457–496.

Baptista, P., Melo, S., & Rolim, C. (2014). Energy, Environmental and Mobility Impacts of Car-sharing Systems. Empirical Results from Lisbon, Portugal. *Procedia - Social and Behavioral Sciences*, 111, 28-37.

Barker, T., Ekins, P., & Foxon, T. (2007). The macro-economic rebound effect and the UK economy. *Energy Policy*, 35(10), 4935-4946.

Barma, N. H., Kaiser, K., Lc, T. M., & Viñuela., L. (2012). *Rents to Riches? The Political Economy of Natural Resource-led Development*. Washington, D.C.: World Bank

Barnes, R. (2009). *Property Rights and Natural Resources*. Hart Publishing.

Barnett, H., & Morse, C. (1965). *Scarcity and Growth: The Economics of Natural Resource Availability*. Washington, D.C.: RFF Press.

Baslar, K. (1998). *The Concept of the Common Heritage of Mankind in International Law*. Brill Nijhoff.

Bastida, A., Ifesi-Okoye, A., Mahmud, S., & Ross, J. (2007). Cross-Border Unitization and Joint Development Agreements: An International Law Perspective. *Houston Journal of International Law*, 29(2), 355–422.

Battery University. (2016). Types of Lithium-ion batteries. Available from: http://batteryuniversity.com/learn/article/types_of_lithium_ion

BCG. (2010). *Winning in emerging market cities: a guide to the world's largest growth opportunity*. Boston Consulting Group.

BCS. (2007). *Mining Industry Energy Bandwidth Study*. Available from: http://energy.gov/sites/prod/files/2013/11/f4/mining_bandwidth.pdf

Beharry, C., & Kuritzky, M. (2015). Going Green: Managing the Environment through International Investment Arbitration. *American University International Law Review*, 30(3), 383–429.

Benvenisti, E. (2002). *Sharing Transboundary Resources: International Law and Optimal Resource Use:* Cambridge University Press.

Berkhout, F., & Hertin, J. (2004). De-materialising and re-materialising: digital technologies and the environment. *Futures*, 36(8), 903-920.

Bértola, L., & Ocampo, J. A. (2012). *Latin America's debt crisis and the "lost decade"*. Institute for the study of the Americas.

Betsill, M. M., & Bulkeley, H. (2004). Transnational Networks and Global Environmental Governance: The Cities for Climate Protection Program. *International Studies Quarterly*, 48(2), 471-493.

Biermann, F., & Pattberg, p. (2008). Global Environmental Governance: Taking Stock, Moving Forward. *Annual Review of Environment and Resources*, 33(1), 277-294.

Biermann, F., Pattberg, P., van Asselt, H., & Zelli, F. (2009). The Fragmentation of Global Governance Architectures: A Framework for Analysis. *Global Environmental Politics*, 9(4), 14-40.

Bilton, M., Aunedi, M., Woolf, M., & Strbac, G. (2014). *Smart appliances for residential demand response. Report A10 for the "Low Carbon London" LCNF project*. London: Imperial College.

BIO Intelligence Service, Institute of Social Ecology, & Sustainable Europe Research Institute. (2012). *Assessment of resource efficiency indicators and targets. Final report prepared for the European Commission, DG Environment*.

Birkeland, J. (2008). *Positive Development: From Vicious Circles to Virtuous Cycles Through Built Environment Design*. London: Earthscan.

Birnie, P., Boyle, A., & Redgwell, C. (2009). *International Law and the Environment, 3rd Edition*. Oxford: Oxford University Press.

BMUB. (2015). *German Resource Efficiency Programme (ProgRess) - programme for the sustainable use and conservation of natural resources. Second Edition (First published 2012)*. Available from: http://www.bmub.bund.de/fileadmin/Daten_BMU/Pools/Broschueren/progress_broschuere_en_bf.pdf

BMWi. (2012). *Germany's new energy policy - heading towards 2050 with secure, affordable and environmentally sound energy.*

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

Berlin: Federal Ministry of Economics and Technology (BMWi).

Boa, E., & Bentley, J. (2009). *Net income change obtained by farmers following advice received from plant health clinics. Impact Assessment Short Report*.

Bodansky, D., Brunnée, J., & Hey, E. (Eds.). (2007). *The Oxford Handbook of International Environmental Law*. Oxford: Oxford University Press.

Bogner, J., Ahmed, M. A., Diaz, C., Faaij, A., Gao, Q., Hashimoto, S., Zhang, T. (2007). Waste Management. In B. Metz, O. R. Davidson, p. R. Bosch, R. Dave, & L. A. Meyer (Eds.), *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Böhringer, C., & Rutherford, T. (2015). *The Circular Economy – an Economic Impact Assessment. Report to SUN-IZA*. Available from: https://sunstiftungsfonds.files.wordpress.com/2015/06/report-circular-economy.pdf

Bos, H. L., Meesters, K. p. H., Conijn, S. G., Corré, W. J., & Patel, M. K. (2016). Comparing biobased products from oil crops versus sugar crops with regard to non-renewable energy use, GHG emissions and land use. *Industrial Crops and Products*, 84, 366-374.

Bossio, D., Dixon, J., Pretty, J. N., Noble, A. D., Hine, R. E., Dixon, J., & Hine, R. E. (2006). Resource-Conserving Agriculture Increases Yields in Developing Countries. *Environmental Science & Technology*, 40(4), 1114-1119.

Botelho, A., Ferreira, P., Lima, F., Pinto, L. M. C., & Sousa, S. (2016). Assessment of the environmental impacts associated with hydropower. *Renewable and Sustainable Energy Reviews*.

Bouwman, L., Goldewijk, K. K., Van Der Hoek, K. W., Beusen, A. H. W., Van Vuuren, D. P., Willems, J., Stehfest, E. (2013). Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900–2050 period. *Proceedings of the National Academy of Sciences*, 110(52), 20882-20887.

Bowman, M., Davies, P., & Redgwell, C. (2010). *Lyster's International Wildlife Law, 2nd Edition*.Cambridge: Cambridge University Press.

Bradley, P., Coke, A., & Leach, M. (2016). Financial incentive approaches for reducing peak electricity demand, experience from pilot trials with a UK energy provider. *Energy Policy, 98*, 108-120.

Bradley, P., Leach, M., & Torriti, J. (2013). A review of the costs and benefits of demand response for electricity in the UK. *Energy Policy, 52*, 312-327.

Braithwaite, J., & Drahos, p. (2000). *Global Business Regulation*. Cambridge: Cambridge University Press.

Brammer, S., & Walker, H. (2011). Sustainable procurement in the public sector: an international comparative study. *International journal of operations & production management*, 31(4), 452-476.

Brasche, S., & Bischof, W. (2005). Daily time spent indoors in German homes – Baseline data for the assessment of indoor exposure of German occupants. *International journal of hygiene and environmental health*, 208(4), 247-253.

Brown, A., & Matlock, M. D. (2011). *A review of water scarcity indices and methodologies*. Available from: https://www.sustainabilityconsortium.org/wp-content/themes/sustainability/assets/pdf/whitepapers/2011_Brown_Matlock_Water-Availability-Assessment-Indices-and-Methodologies-Lit-Review.pdf

Bruinsma, J. (2009). *The Resource Outlook to 2050: By how much do land, water, and crop yields need to increase by 2050?* Paper presented at the FAO Expert Meeting, 24-26 June 2009, on "How to Feed the World in 2050". Rome: FAO.

BSHF. (2013). World Habitat Awards, Winners and Finalists, Green Mortgage. Available from: https://www.bshf.org/world-habitat-awards/winners-and-finalists/green-mortgage/

Buckwell, A., Nordang Uhre, A., Williams, A., Polakova, J., Blum, W., Schifer, J., ... Haber, W. (2014). *The sustainable intensification of European Agriculture. A review sponsored by the RISE foundation*. Brussels: RISE Foundation.

Bulkeley, H., Broto, V., Maassen, A., & Castan Broto, V. (2014). Low-carbon Transitions and the Reconfiguration of Urban Infrastructure. *Urban Studies, 51*(7), 1471-1486.

Bulkeley, H., Castán Broto, V., Hodson, M., & Marvin, S. (2011). Cities and the Low Carbon Transition. *The European Financial Review* (August-September), 24-27.

Bulkeley, H., & Gregson, N. (2009). Crossing the threshold: municipal waste policy and household waste generation. *Environment and planning A, 41*(4), 929-945.

Burgin, S., & Webb, T. (2011). 'Water metres': a new approach to thinking about water conservation in suburbia. *Urban Water Journal*, 8(4), 233-240.

Buzby, J. C., Farah-Wells, H., & Hyman, J. (2014). The estimated amount, value, and calories of postharvest food losses at the retail and consumer levels in the United States. *USDA-ERS Economic Information Bulletin*.

Campbell, B., Khachatryan, H., Behe, B., Hall, C., & Dennis, J. (2016). Crunch the can or throw the bottle? Effect of "bottle deposit laws" and municipal recycling programs. *Resources, Conservation and Recycling, 106*, 98-109.

Carruth, M., & Allwood, J. (2012). The development of a hot rolling process for variable cross-Section I-beams. *Journal of materials processing technology, 212*(8), 1640-1653.

Castellani, V., Sala, S., & Mirabella, N. (2015). Beyond the throwaway society: A life cycle-based assessment of the environmental benefit of reuse. *Integrated Environmental Assessment and Management, 11*(3), 373-382.

Castillo, G. E., Le, M. N., & Pfeifer, K. (2012). *Oxfam America: Learning from the System of Rice Intensification in Northern Vietnam*. Washington, D.C.: International Food Policy Research Institute.

CBD. (1992). Convention on Biological Diversity (CBD), adopted 5 June 1992, in force 29 December 1993, 1760 UNTS 79.

CBD, & GEF. (2012). *Marine Spatial Planning in the Context of the Convention on Biological Diversity: A study carried out in response to CBD COP 10 decision X/29. Secretariat of the Convention on Biological Diversity (CBD) and the Scientific and Technical Advisory Panel — GEF. Technical Series No. 68*. Washington, D.C.: GEF.

CCC. (2013). *Fourth carbon budget review - Part 2: the cost effective path to the 2050 target*. London: Committee on Climate Change.

CCC. (2014). *Meeting carbon budgets - 2014 progress report to Parliament*. London: Committee on Climate Change.

CE, & BioIS. (2014). *Study on modelling of the economic and environmental impacts of raw material consumption*. Available from: http://ec.europa.eu/environment/enveco/resource_efficiency/pdf/RMC.pdf

Cervero, R., & Dai, D. (2014). BRT TOD: Leveraging transit oriented development with bus rapid transit investments. *Transport Policy, 36*, 127-138.

Cervero, R., & Kang, C. D. (2011). Bus rapid transit impacts on land uses and land values in Seoul, Korea. *Transport Policy, 18*(1), 102-116.

Cervero, R., & Murakami, J. (2009). Rail and Property Development in Hong Kong: Experiences and Extensions. *Urban Studies, 46*(10), 2019-2043.

Cervero, R., & Sullivan, C. (2011). Green TODs: marrying transit-oriented development and green urbanism. *International Journal of Sustainable Development and World Ecology*, 18(3), 210-218.

CGG. (1995). *Our Global Neighbourhood. The Report of the Commission on Global Governance*. Oxford: Oxford University Press.

Chaplin Kramer, R., Sharp, R., Mandle, L., Sim, S., Johnson, J., Butnar, I., ... Kareiva, p. (2015). Spatial patterns of agricultural expansion determine impacts on biodiversity and carbon storage. *Proceedings of the National Academy of Sciences of the United States of America*, 112(24), 7402-7407.

Charles, A. (2012). People, oceans and scale: governance, livelihoods and climate change adaptation in marine social–ecological systems. *Current Opinion in Environmental Sustainability, 4*(3), 351–357.

Chavez, A., & Ramaswami, A. (2013). Articulating a trans-boundary infrastructure supply chain greenhouse gas emission footprint for cities: Mathematical relationships and policy relevance. *Energy Policy, 54*, 376-384.

Chertow, M. (2000). Industrial Symbiosis: Literature and Taxonomy. *Annual review of energy and the environment, 25*(1), 313-337.

Chester, M., & Horvath, A. (2009). Environmental assessment of passenger transportation should include infrastructure and supply chains. *Environmental Research Letters, 4*(2), 024008.

Chester, M., Pincetl, S., Elizabeth, Z., Eisenstein, W., & Matute, J. (2013). Infrastructure and automobile shifts: positioning transit to reduce life-cycle environmental impacts for urban sustainability goals. *Environmental Research Letters, 8*(1), 015041.

Christmann, P., Gloaguen, E., Labbé, J.-F., Melleton, J., & Piantone, p. (2015). Chapter 1 - Global Lithium Resources and Sustainability Issues A2 - Chagnes, Alexandre. In J. Światowska (Ed.), *Lithium Process Chemistry* (pp. 1-40). Amsterdam: Elsevier.

CIA. (2016). Central Intelligence Agency. The World Factbook. Available from: https://www.cia.gov/library/publications/the-world-factbook/

Clark, D. A. (2014). Defining and Measuring Human Well-Being. In B. Freedman (Ed.), *Global Environmental Change* (pp. 833-855). Dordrecht: Springer Netherlands.

Coady, D., Parry, I., Sears, L., & Shang, B. (2015). *How Large Are Global Energy Subsidies?* Available from: https://www.imf.org/external/pubs/cat/longres.aspx?sk=42940.0

Coll, M., Shannon, L. J., Kleisner, K. M., Juan-Jorda, M. J., Bundy, A., Juan Jordá, M. J., ... Zador, S. G. (2016). Ecological indicators to capture the effects of fishing on biodiversity and conservation status of marine ecosystems. *Ecological indicators, 60*, 947-962.

Commoner, B. (1972). The environmental cost of economic growth. In R. G. Ridker (Ed.), *Population, Resources and the Environment* (pp. 339–363). Washington, D.C.: Government Printing Office.

Comprehensive Assessment of Water Management in Agriculture. (2007). *Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture*. London and Colombo: Earthscan and International Water Management Institute.

Cotula, L. (2013). *The Great African Land Grab? Agricultural Investments and the Global Food System*. London: Zed Books.

Cotula, L., Oya, C., Codjoe, E. A., Eid, A., Kakraba-Ampeh, M., Keeley, J., ... Rizzo, M. (2014). Testing Claims about Large Land Deals in Africa: Findings from a Multi-Country Study. *Journal of Development Studies*, 50(7), 903-925.

Cotula, L., Vermeulen, S., Leonard, R., & Keeley, J. (2009). *Land grab or development opportunity? Agricultural investment and international land deals in Africa*. Rome: FAO / International Institute for Environment and Development/ International Fund for Agricultural Development.

Resource Efficiency: Potential and Economic Implications • International Resource Panel Report

Craik, N. (2011). *The International Law of Environmental Impact Assessment: Process, Substance and Integration*. Cambridge: Cambridge University Press.

CREST. (2013). *The Case for Responsible Travel: Trends and Statistics*. Available from: http://www.responsibletravel.org/whatWeDo/certificationAndMarketStudies.php

CREST. (n.d.). *Responsible Travel: Global Trends & Statistics*. Available from: http://www.responsibletravel.org/news/fact_sheets/fact_sheet_-_global_ecotourism.pdf

Dahlström, K., & Ekins, p. (2005). Eco-efficiency Trends in the UK Steel and Aluminum Industries. *Journal of Industrial Ecology*, 9(4), 171-188.

Dalgaard, R., Schmidt, J., Halberg, N., Christensen, P., & Thrane, M. (2008). LCA of soybean meal. *The International Journal of Life Cycle Assessment*, 13(3), 240-254.

Darby, S. (2010). *Natural resource governance: New frontiers in transparency and accountability*. Transparency Accountability Initiative.

Davis, S., & Caldeira, K. (2010). Consumption-based accounting of CO_2 emissions. *Proceedings of the National Academy of Sciences of the United States of America*, 107(12), 5687-5692.

De Fraiture, C., Fayrap, A., Unver, O., & Ragab, R. (2014). Integrated water management approaches for sustainable food production. *Irrigation and Drainage*, 63, 221-231.

De Long, J. B. (1998). *Estimates of World GDP, One Million B.C. - present*. Available from: http://delong.typepad.com/print/20061012_LRWGDP.pdf

de Strasser, L., Howells, M., Alfstad, T., Rogner, H., Welsch, M., & Lipponen, A. (2014). *Water-Food-Energy-Ecosystems Nexus: Reconciling Different Uses in Transboundary River Basins. UNECE Water Convention, Draft Methodology for the Nexus Assessment for discussion, version 1 September 2014*. Available from: https://www.unece.org/fileadmin/DAM/env/documents/2014/WAT/09Sept_8-9_Geneva/Methodology_1Sept2014_clean_forWeb.pdf

De T´Serclaes, p. (2007). *Financing Energy Efficient Homes. Existing Policy Responses to Financial Barriers. IEA Information Paper*. Available from: http://www.iea.org/publications/freepublications/publication/FinancialBarrierBuilding-1.pdf

de Vries, S. C., van de Ven, G. W. J., & van Ittersum, M. K. (2014). First or second generation biofuel crops in Brandenburg, Germany? A model-based comparison of their production-ecological sustainability. *European Journal of Agronomy, 52, Part B*, 166-179.

Deininger, K., & Ali, D. A. (2008). Do Overlapping Land Rights Reduce Agricultural Investment? Evidence from Uganda. *American Journal of Agricultural Economics*, 90(4), 869–882.

Deng, Z., Carlson, T., Duncan, J., Richmond, M., & Dauble, D. (2010). Use of an autonomous sensor to evaluate the biological performance of the advanced turbine at Wanapum Dam. *Journal of renewable and sustainable energy, 2*(5), 053104.

DeSimone, L., & Popoff, F. (1996). *Eco-efficiency: the Business Link to Sustainable Development*. Cambridge, MA / London: MIT Press.

Despeisse, M., & Ford, S. (2015). *The role of additive manufacturing in improving resource efficiency and sustainability*. Cambridge: Centre for Technology Management, University of Cambridge.

Dicken, p. (2011). *Global shift: mapping the changing contours of the world economy, 6th edition*. New York: The Guilford Press.

Dingwerth, K., & Pattberg, p. (2006). Global Governance as a Perspective on World Politics. *Global Governance: A Review of Multilateralism and International Organizations, 12*(2), 185-203.

Dissanayake, G., & Sinha, p. (2015). An examination of the product development process for fashion remanufacturing. *Resources, Conservation and Recycling, 104, Part A*, 94-102.

Dittrich, M., Bringezu, S., Schuetz, H., & Schütz, H. (2012). The physical dimension of international trade, Part 2: Indirect global resource flows between 1962 and 2005. *Ecological Economics, 79*, 32-43.

Dobbs, R., Oppenheim, J., Thompson, F., Brinkman, M., & Zornes, M. (2011). *Resource Revolution: Meeting the world's energy, materials, food, and water needs*. McKinsey Global Institute, McKinsey Sustainability and Resource Productivity Practice.

DoETR. (1995). *Making waste work; a strategy for sustainable waste management in England and Wales*. London, UK: Department of the Environment, Transport and the Regions.

Dolan, C., & Humphrey, J. (2000). Governance and Trade in Fresh Vegetables: The Impact of UK Supermarkets on the African Horticulture Industry. *Journal of Development Studies*, 37(2), 147.

Donahue, J. D., & Nye Jr., J. S. (Eds.). (2000). *Governance in a Globalizing World*. Washington, D.C.: Brookings Institution.

Dones, R., Heck, T., Faist Emmenegger, M., & Jungbluth, N. (2004). *Life Cycle Inventories for the Nuclear and Natural Gas Energy Systems, and Examples of Uncertainty Analysis (14 pp)* (Vol. 10).

Dong, H., Ohnishi, S., Fujita, T., Geng, Y., Fujii, M., & Dong, L. (2014). Achieving carbon emission reduction through industrial & urban symbiosis: A case of Kawasaki. *Energy*, 64, 277-286.

Dong, J., Xue, G., & Li, R. (2016). Demand response in China: Regulations, pilot projects and recommendations – A review. *Renewable and Sustainable Energy Reviews*, 59, 13-27.

DOT. (2015). *Freight facts and figures 2015*. Washington, D.C.: US Department of Transportation, Bureau of Transportation Statistics.

Dou, Z., Ferguson, J. D., Galligan, D. T., Kelly, A. M., Finn, S. M., & Giegengack, R. (2016). Assessing US food wastage and opportunities for reduction. *Global Food Security, 8*, 19-26.

Dowling, R., & Kent, J. (2015). Practice and public–private partnerships in sustainable transport governance: The case of car sharing in Sydney, Australia. *Transport Policy, 40*, 58-64.

Driscoll, C., Mason, R., Chan, H., Jacob, D., & Pirrone, N. (2013). Mercury as a Global Pollutant: Sources, Pathways, and Effects. *Environmental Science & Technology, 47*(10), 4967-4983.

Du, p. (2015). Chapter 4 - Application of Energy Storage for Fast Regulation Service in Energy. *Market Energy Storage for Smart Grids* (pp. 97-113). Boston: Academic Press.

du Plessis, C. (2001). Sustainability and sustainable construction: the African context. *Building research and information, 29*(5), 374-380.

Dudley, N. (Ed.) (2008). *Guidelines for applying protected area management categories*. Gland, Switzerland: IUCN.

EBRD. (2014). *European Bank for Reconstruction and Development Annual Report 2014*. London: EBRD.

EC. (2011a). *'Analysis associated with the Roadmap to a Resource Efficient Europe Part I', SEC(2011) 1068 final, 20.9.2011, Commission Staff Working Paper accompanying the document 'Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of Regions Roadmap to a Resource Efficient Europe', COM(2011) 571 final*. Available from: http://ec.europa.eu/environment/resource_efficiency/pdf/working_paper_part1.pdf

EC. (2011b). *'Analysis associated with the Roadmap to a Resource Efficient Europe Part II', SEC(2011) 1067 final, 20.9.2011, Commission Staff Working Paper accompanying the document 'Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of Regions Roadmap to a Resource Efficient Europe', COM(2011) 571 final*. Available from: http://ec.europa.eu/environment/resource_efficiency/pdf/working_paper_part2.pdf

EC. (2011c). *Commission Staff Working Paper: Analysis associated with the Roadmap to a Resource Efficient Europe Parts I and II. Brussels, 20.9.2011 SEC(2011) 1067 final*. Brussels: European Commission.

EC. (2011d). *A resource-efficient Europe – Flagship initiative under the Europe 2020 Strategy. Communication from the Commission to the European Parliament, The Council, The European Economic and Social Committee and the Committee of the Regions. Brussels, 26.1.2011 COM(2011) 21*. Brussels: European Commission.

EC. (2014). *Towards a circular economy: A zero waste programme for Europe, Communication COM(2014) 398 final, July 2*. Brussels: European Commission.

EC. (2015a). *Closing the loop – An EU Action Plan for the Circular Economy, COM(2015) 614 final*. Available from: http://ec.europa.eu/environment/circular-economy/index_en.htm

EC. (2015b). EU Resource Efficiency Scoreboard 2015. Available from: http://ec.europa.eu/environment/resource_efficiency/targets_indicators/scoreboard/pdf/EU%20Resource%20Efficiency%20Scoreboard%202015.pdf

EC, IMF, OECD, UN, & World Bank. (2009). System of National Accounts 2008.

EEA. (1999). *Making sustainability accountable: Eco-efficiency, resource productivity and innovation. Topic Report No. 11/1999*. Copenhagen: European Environment Agency.

EEA. (2011a). *Earnings, jobs and innovation: the role of recycling in a green economy*. Available from: http://www.eea.europa.eu/publications/earnings-jobs-and-innovation-the

EEA. (2011b). *Global governance – the rise of non-state actors: A background report for the SOER 2010 assessment of global megatrends. EEA Technical report No 4/2011*. Copenhagen: European Environment Agency.

EEA. (2011c). *Resource Efficiency in Europe: Policies and approaches in 31 EEA member and cooperating countries*. Available from: http://www.eea.europa.eu/publications/resource-efficiency-in-europe

EEA. (2015). *Annual European Union greenhouse gas inventory 1990–2013 and inventory report 2015*. Copenhagen: European Environment Agency.

Ehrlich, p. R., & Holdren, J. p. (1971). Impact of Population Growth. *Science, 171*(3977), 1212-1217.

EIA. (2013). *International Energy Outlook, 2013*. Available from: www.eia.gov/forecasts/ieo/pdf/0484(2013).pdf

EIA. (2016). Motor gasoline consumption expected to remain below 2007 peak despite increase in travel. Available from: http://www.eia.gov/todayinenergy/detail.cfm?id=25072

Ekins, p. (2012). Safeguarding the Future of the Wealth of Nature: Sustainability, Substitutability, Measurement, Thresholds and Aggregation Issues in Natural Capital Accounting for Human Well-Being. In UNU-IHDP & UN Environment (Eds.), *The Inclusive Wealth Report: Measuring Progress Towards Sustainability* (pp. 231-266). Cambridge: Cambridge University Press.

Elliott, J., Firbank, L. G., Drake, B., Cao, Y., & R. Gooday. (2013). *Exploring the Concept of Sustainable Intensification. Report to the Land Use Policy Group*. Wolverhampton: Agricultural Development Advisory Service.

Ellis, F., & Biggs, S. (2001). Evolving Themes in Rural Development 1950s–2000s. *Development Policy Review, 19*(4), 437–448.

EMF. (2015). *Growth Within: a Circular Economy Vision for a Competitive*

Europe. Cowes, United Kingdom: Ellen MacArthur Foundation.

EMF. (2016a). Case studies. France: Collaborative textiles recycling initiative. Available from: http://www.ellenmacarthurfoundation.org/case-studies/france-collaborative-textiles-recycling-initiative

EMF. (2016b). Circular Economy. Available from: http://www.ellenmacarthurfoundation.org/circular-economy

Energy and Climate Partnership of America. (2012). *INFONAVIT–Achievements on the Residential Green Mortgage Program.* Paper presented at the Energy Efficiency Working Group Workshop, March 21-22, 2012.

European Parliament. (2012). *Resource Efficiency in European Industry.* Available from: http://www.europarl.europa.eu/RegData/etudes/etudes/join/2012/492457/IPOL-ITRE_ET(2012)492457_EN.pdf

Environmental Protection Agency (EPA). (2015). *Inventory of US Greenhouse Gas Emissions and Sinks: 1990-2013 (April 2015).* Washington: Environmental Protection Agency.

EPOMM. (2016). TEMS - The EPOMM Modal Split Tool. Available from: http://www.epomm.eu/tems/index.phtml

Erbel, H. (2008). A best practice example of chemical leasing in metal cleaning in the automotive industry. Report by an Austrian company. In T. Jakl & p. Schwager (Eds.), *Chemical leasing goes global. Selling services instead of barrels: a win-win business model for environment and industry*. Vienna: UNIDO.

Esselman, P., & Opperman, J. (2010). Overcoming Information Limitations for the Prescription of an Environmental Flow Regime for a Central American River. *Ecology and Society, 15*(1).

EU Switch-Asia. (2014). *Zero Carbon Resorts: Cutting carbon, saving energy, resources and money with appropriate technologies, Impact Sheet.* EU Switch-Asia.

EUROSTAT. (2013). *Economy-wide material flow accounts. Compilation guide 2013.* Luxembourg: European Office of Statistics.

Everett, T., Ishwaran, M., Ansaloni, G. P., & Rubin, A. (2010). *Economic Growth and the Environment', Defra Evidence and Analysis Series, Paper 2.* Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/69195/pb13390-economic-growth-100305.pdf

Faberi, S., Paolucci, L., Lapillonne, B., & Pollier, K. (2012). *Trends and policies for energy savings and emissions in transport.* Available from: http://www.odyssee-mure.eu/publications/br/energy-efficiency-trends-policies-transport.pdf

Fagnant, D., & Kockelman, K. (2014). The travel and environmental implications of shared autonomous vehicles, using agent-based model scenarios. *Transportation research. Part C, Emerging technologies, 40*, 1-13.

FAO. (2011a). *Energy-smart food for people and climate: issue paper.* Available from: http://www.fao.org/docrep/014/i2454e/i2454e00.pdf

FAO. (2011b). *SAVE and GROW: A policymaker's guide to the sustainable intensification of smallholder crop production.* Rome: FAO.

FAO. (2011c). *The state of the world's land and water resources for food and agriculture (SOLAW) - Managing systems at risk.*

FAO. (2012a). *Improving Food Systems for Sustainable Diets in a Green Economy, FAO GEA Rio+20 Working Paper 4: Utilization.* Available from: http://www.fao.org/fileadmin/templates/ags/docs/SFCP/WorkingPaper4.pdf

FAO. (2012b). *Voluntary guidelines on the responsible governance of tenure of land, fisheries and forests in the context of national food security.* Available from: http://www.fao.org/docrep/016/i2801e/i2801e.pdf

FAO. (2012c). *World Agriculture towards 2030/2050: the 2012 Revision. ESA Working Paper No. 12-03.* Rome: FAO.

FAO. (2014a). *Agriculture, forestry and other land use emissions by sources and removals by sinks.* vailable from: http://www.fao.org/docrep/019/i3671e/i3671e.pdf

FAO. (2014b). *State of Food and Agriculture: Innovation in family farming.* Rome: FAO.

FAO. (2014c). *The Water-Energy-Food Nexus. A new approach in support of food security and sustainable agriculture.* Olivier Dubois, Jean-Marc Faurès, Erika Felix, Alessandro Flammini, Jippe Hoogeveen, Lucie Pluschke, Manas Puri and Olçay Ünver. Available from: http://www.fao.org/nr/water/docs/FAO_nexus_concept.pdf

FAO. (2015a). GLADIS - Global land degradation information system. Available from: http://www.fao.org/nr/lada/gladis/gladis/

FAO. (2015b). Soil is a non-renewable resource (fact sheet). Rome: FAO.

FAO. (2015c). T*he State of Food Insecurity in the World - Meeting the 2015 international hunger targets: taking stock of uneven progress.* Rome: FAO.

FAO. (2015d). *Status of the World's Soil Resources.* Rome: FAO.

FAO. (2016a). FAOSTAT: *Food and Agriculture Organisation of the United Nations Statistics Division.* Available from: http://faostat3.fao.org/home/E

FAO. (2016b). *The State of World Fisheries and Aquaculture 2016. Contributing to food security and nutrition for all.* Rome: FAO.

FAO. (2017). FAOSTAT. Available from: http://www.fao.org/faostat/en/#data

Feedback. (2015). *Food waste in Kenya: uncovering food waste in the horticultural export supply chain.* London: Feedback.

Ferrer, G. (1997). *The economics of tire remanufacturing. Resources, Conservation and Recycling, 19*(4), 221-255.

Finer, M., Jenkins, C., & Krkosek, M. (2012). Proliferation of Hydroelectric Dams in the Andean Amazon and Implications for Andes-Amazon Connectivity. *PLoS One, 7*(4), e35126-e35126.

Fischer-Kowalski, M., & Haberl, H. (Eds.). (2007). *Socioecological Transitions and Global Change: Trajectories of Social Metabolism and Land Use.* Cheltenham Edward Elgar.

Fischer-Kowalski, M., Krausmann, F., Giljum, S., Lutter, S., Mayer, A., Bringezu, S., ... Weisz, H. (2011). Methodology and Indicators of Economy-wide Material Flow Accounting. *Journal of Industrial Ecology, 15*(6), 855-876.

FOEN. (2011). *Marrakech Task Force on Sustainable Public Procurement Lead by Switzerland. Activity Report.* Available from: http://www.unep.fr/scp/procurement/docsres/projectinfo/MTFonSPPReportCSD19FINAL.pdf

Fogelholm, M. (2013). New Nordic Nutrition Recommendations are here. *Food & Nutrition Research; Vol 57 (2013) incl Supplements.*

Francie, K. A., Jean-Pierre, K., Pierre, D., Victor, S., & Vladimir, p. (2015). Stochastic models and numerical solutions for manufacturing/remanufacturing systems with applications to the printer cartridge industry. *Journal of Manufacturing Systems, 37, Part 3*, 662-671.

Fritsche, U., Gavilan, I., & Leagnavar, p. (2013). *Elaborating the International Discussion on Resource Efficiency (ENTIRE): Part I: Resource Efficiency Policies in Various Countries - Annex Report.* Prepared for IFAD with funding from BMBF.

Fuhry, L., & Wells, W. (2013). Green Goes Mainstream in Low-Income Housing. *Planning, 79*(9), 31-37.

G7. (2015). *Leaders' Declaration. G7 Summit, 7-8 June 2015.* Available from: https://www.g7germany.de/Content/EN/_Anlagen/G7/2015-06-08-g7-abschluss-eng_en.pdf

Galaz, V., Moberg, F., Olsson, E. K., Paglia, E., & Parker, C. (2010). Institutional and Political Leadership Dimensions of Cascading Ecological Crises. *Public Administration, 89*, 361–380.

Gallagher, K., & Shrestha, E. (2011). Investment Treaty Arbitration and Developing Countries: A Re-Appraisal. *Journal of World investment and Trade, 12*, 919–928.

Gallo, A. B., Simões-Moreira, J. R., Costa, H. K. M., Santos, M. M., & Moutinho dos Santos, E. (2016). Energy storage in the energy transition context: A technology review. *Renewable and Sustainable Energy Reviews, 65*, 800-822.

Garnaut, R. (2008). *The Garnaut Climate Change Review, Final Report.* Port Melbourne: Cambridge University Press.

GBPN. (2014). *Residential Buildings in India: Energy Use Projections and Savings Potentials.* Available from: http://www.gbpn.org/newsroom/report-residential-buildings-india-energy-use-projections-and-savings-potentials

Gemmill, B., & Bamidele-Izu, A. (2002). The Role of NGOs and Civil Society in Global Environmental Governance. In D. C. Esty & M. H. Ivanova (Eds.), Global Environmental Governance: Options and Opportunities. Yale Center for Environmental Law & Policy.

Geoscience Australia. (2017). Maritime Boundary Definitions. Available from: http://www.ga.gov.au/scientific-topics/marine/jurisdiction/maritime-boundary-definitions

Gereffi, G., Humphrey, J., & Sturgeon, T. (2005). The governance of global value chains. *Review of International Political Economy, 12*(1), 78–104.

German Law Archive. (2013). Closed Substance Cycle Waste Management Act (Kreislaufwirtschafts- und Abfallgesetz, KrW-/AbfG) – zExcerpts. Available from: http://germanlawarchive.iuscomp.org/?p=303

Geth, F., Brijs, T., Kathan, J., Driesen, J., & Belmans, R. (2015). An overview of large-scale stationary electricity storage plants in Europe: Current status and new developments. *Renewable and Sustainable Energy Reviews, 52*, 1212-1227.

Gharfalkar, M., Court, R., Campbell, C., Ali, Z., & Hillier, G. (2015). Analysis of waste hierarchy in the European waste directive 2008/98/EC. *Waste Management, 39*, 305-313.

Ghaus-Pasha, A. (2005). *The Role of Civil Society Organisations in Governance.* Paper presented at the 6th Global Forum on Reinventing Government Towards Participatory and Transparent Governance, 24-27 May 2005, Seoul, Republic of Korea. http://unpan1.un.org/intradoc/groups/public/documents/un/unpan019594.pdf

Ghavami, K. (2005). Bamboo as reinforcement in structural concrete elements. *Cement & concrete composites, 27*(6), 637-649.

Gilson, G. (2012). Corporate Social Responsibility in the extractive industries: Experiences from developing countries. *Resources Policy, 37*(2), 131-137.

Girardet, H. (1992). *The Gaia atlas of cities: new directions for sustainable urban living.* London: Gaia Books.

Girardet, H. (2004). *Cities, People, Planet.* Chichester: John Wiley & Sons, Ltd.

Gleeson, T., Wada, Y., Bierkens, M. F. P., & van Beek, L. p. H. (2012). Water balance of global aquifers revealed by groundwater footprint. *Nature, 488*(7410), 197-200.

Gleick, p. (2002). Water management: Soft water paths. *Nature, 418*(6896), 373-373.

Gleick, p. H. (2001). Safeguarding our water - Making every drop count. *Scientific American, 284*(2), 40-45.

Golev, A., Corder, G. D., & Giurco, D. p. (2014). Industrial symbiosis in Gladstone: a decade of progress and future development. *Journal of Cleaner Production, 84*, 421-429.

Gordon, K., & Pohl, J. (2011). *Environmental Concerns in International Investment Agreements: A Survey. OECD Working Papers on International Investment, 2011/01.* Paris, France: OECD Publishing.

Gordon, R. B., Bertram, M., & Graedel, T. E. (2006). Metal stocks and sustainability. *Proceedings of the National Academy of Sciences, 103*(5), 1209-1214.

Graedel, T. E., & Reck, B. (2016). Six Years of Criticality Assessments: What Have We Learned So Far? *Journal of Industrial Ecology, 20*(4), 692-699.

Greenblatt, J. B., & Saxena, S. (2015). Autonomous taxis could greatly reduce greenhouse-gas emissions of US light-duty vehicles. *Nature Clim. Change, 5*(9), 860-863.

GTZ, CSCP, & Wuppertal Institute for Climate, E. a. E. (2006). *Policy Instruments for Resource Efficiency: Towards Sustainable Consumption and Production*. Berlin: GTZ.

Guide, V. D. R., & Van Wassenhove, L. N. (2009). OR FORUM—The Evolution of Closed-Loop Supply Chain Research. *Operations Research, 57*(1), 10-18.

Gump, B., MacKenzie, J., Dumas, A., Palmer, C., Parsons, P., Segu, Z., ... Bendinskas, K. (2012). Fish consumption, low-level mercury, lipids, and inflammatory markers in children. *Environmental research, 112*, 204-211.

Günter, N., & Marinopoulos, A. (2016). Energy storage for grid services and applications: Classification, market review, metrics, and methodology for evaluation of deployment cases. *Journal of Energy Storage, 8*, 226-234.

Guo, W.-x., Wang, H.-x., Xu, J.-x., & Xia, Z.-q. (2011). Ecological operation for Three Gorges Reservoir. *Water Science and Engineering, 4*(2), 143-156.

Gustavsson, J., Cederberg, C., Sonesson, U., van Otterdijk, R., & Meybeck, A. (2011). *Global food losses and food waste - extent, causes and prevention.* Rome: FAO.

Guttikunda, S., Begum, B., & Wadud, Z. (2013). Particulate pollution from brick kiln clusters in the Greater Dhaka region, Bangladesh. *Air Quality, Atmosphere & Health, 6*(2), 357-365.

Haarman, A. (2015). *Towards sustainable plastic recycling in India - experiences from the field.* Available from: http://sustainable-recycling.org/sustainable-recycling/wp-content/uploads/2015/08/Haarman_2015_SRI-India.pdf

Haberl, H., Erb, K.-H., & Krausmann, F. (2014). Human Appropriation of Net Primary Production: Patterns, Trends, and Planetary Boundaries. *Annual Review of Environment and Resources, 39*(1), 363-391.

Hanna, S., Folke, C., & Maler, K.-G. (Eds.). (1996). *Rights to Nature: Ecological, Economic, Cultural, and Political Principles of Institutions for the Environment.* Washington, D.C.: Island Press.

Hanslow, K., Gunasekera, D., Cullen, B., & Newth, D. (2014). Economic impacts of climate change on the Australian dairy sector. *Australian Journal of Agricultural and Resources Economics, 58*(1), 60-77.

Hanson, B., & May, D. (2011). *Drip irrigation salinity management for row crops.* Available from: http://anrcatalog.ucanr.edu/pdf/8447.pdf

Harrabin, R. (2013). Chill out, save energy, no sweat. *BBC News.* Available from: http://wwwnews.live.bbc.co.uk/news/science-environment-23343211

Harris, p. G. (Ed.) (2016). *Routledge Handbook of Global Environmental Politics:* Routledge

Hatfield-Dodds, S., Adams, p. D., Brinsmead, T. S., Bryan, B. A., Chiew, F. H. S., Finnigan, J. J., ... Wonhas, A. (2015). *Australian National Outlook 2015: Economic activity, resource use, environmental performance and living standards, 1970-2050.* Canberra: CSIRO.

Hatfield-Dodds, S., Schandl, H., Adams, p. D., Baynes, T. M., Brinsmead, T. S., Bryan, B. A., ... Wonhas, A. (2015). Australia is 'free to choose' economic growth and falling environmental pressures. *Nature, 527*(7576), 49-53.

Hatfield-Dodds, S., Schandl, H., Newth, D., Obersteiner, M., Cai, Y., Baynes, T., ... Havlik, p. (2017). Assessing global resource use and greenhouse emissions to 2050, with ambitious resource efficiency and climate mitigation policies. *Journal of Cleaner Production.*

Haufler, V. (2010). Disclosure as Governance: The Extractive Industries Transparency Initiative and Resource Management in the Developing World. *Global Environmental Politics, 10*(3), 53–73.

Hawkins, T. R., Singh, B., Majeau-Bettez, G., & Strømman, A. H. (2013). Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles. *Journal of Industrial Ecology, 17*(1), 53-64.

Heinonen, J., & Junnila, S. (2011). A Carbon Consumption Comparison of Rural and Urban Lifestyles. *Sustainability, 3*(8), 1234.

Heinzle, S. L., & Wüstenhagen, R. (2012). Dynamic Adjustment of Eco-labeling Schemes and Consumer Choice – the Revision of the EU Energy Label as a Missed Opportunity? *Business Strategy and the Environment, 21*(1), 60-70.

Henson, S., & Reardon, T. (2005). Private agri-food standards: Implications for food policy and the agri-food system *Food Policy*, 30, 241–253.

Herrick, J. E., Beh, A., Barrios, E., Bouvier, I., Coetzee, M., Dent, D., ... Webb, N. p. (2016). The Land-Potential Knowledge System (LandPKS): mobile apps and collaboration for optimizing climate change investments. *Ecosystem Health and Sustainability, 2*(3).

Herring, H., & Sorrell, S. (Eds.). (2009). *Energy Efficiency and Sustainable Consumption: the Rebound Effect.* Basingstoke/New York: Palgrave Macmillan.

Hillman, T., Janson, B., & Ramaswami, A. (2011). Spatial Allocation of Transportation Greenhouse Gas Emissions at the City Scale. *Journal of Transportation Engineering, 137*(6), 416-425.

Hillman, T., & Ramaswami, A. (2010). Greenhouse Gas Emission Footprints and Energy Use Benchmarks for Eight US Cities. *Environmental Science & Technology, 44*(6), 1902-1910.

HLPE. (2014). *Food losses and waste in the context of sustainable food systems. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security.* Rome: HLPE.

HLPE. (2015). *Water for food security and nutrition. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security.* Rome: HLPE.

HLTF. (2012). *Food and Nutrition Security for All through Sustainable Agriculture and Food Systems. Note from the United Nations System High Level Task Force on Global Food Security.* Available from: http://un-foodsecurity.org/sites/default/files/SustainableAgricultureFoodSystems.pdf

HM Parliament (2008). Climate Change Act 2008. Parliament of the United Kingdom.

Hodson, M., Marvin, S., Robinson, B., & Swilling, M. (2012). Reshaping Urban Infrastructure. *Journal of Industrial Ecology, 16*(6), 789-800.

Hoekstra, A. Y., & Chapagain, A. K. (2007). Water footprints of nations: Water use by people as a function of their consumption pattern. *Water Resources Management, 21*(1), 35-48.

Hoff, H. (2011). *Understanding the Nexus. Background Paper for the Bonn 2011Conference: The Water, Energy and Food Security Nexus.* Stockholm: Stockholm Environment Institute.

Hoffmann, I. (2010). Climate change and the characterization, breeding and conservation of animal genetic resources. *Animal Genetics, 41*, 32-46.

Hogg, N., & Jackson, T. (2009). Digital Media and Dematerialization. *Journal of Industrial Ecology, 13*(1), 127-146.

Holden, J., & Pagel, M. (2013). *Transnational land acquisitions: What are the drivers, levels, and destinations of recent transnational land acquisitions?* EPS-PEAKS Consortium.

Holttinen, H., Meibom, P., Orths, A., Lange, B., O'Malley, M., Tande, J. O., ... Hulle, F. v. (2009). *Impacts of large amounts of wind power on design and operation of power systems, results of IEA collaboration.* Paper presented at the 8th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks of Offshore Wind Farms, Bremen.

Hossain, M., & Abdullah, A. M. (2012). Securing the Environment: Potentiality of Green Brick in Bangladesh. *Bangladesh University of Professionals Journal, 1*(1), 79-89.

Huang, R., Riddle, M., Graziano, D., Warren, J., Das, S., Nimbalkar, S., ... Masanet, E. Energy and emissions saving potential of additive manufacturing: the case of lightweight aircraft components. *Journal of Cleaner Production.*

Huang, Z., Zhang, C., & Wu, Y. (2012). Bamboo Strengthened with Carbon Fiber Reinforced Polymer for the Substitutes of Steel Substructures. *Novel and non-conventional materials and technologies for sustainability. Key engineering materials, 517*, 233-237.

Hubacek, K., Guan, D., & Barua, A. (2007). Changing lifestyles and consumption patterns in developing countries: A scenario analysis for China and India. *Futures, 39*(9), 1084-1096.

Hueting, R. (1992). Growth, Environment and National Income: Theoretical Problems and a Practical Solution. In p. Ekins & M. Max-Neef (Eds.), *Real-Life Economics: Understanding Wealth Creation* (pp. 255-263). London / New York: Routledge.

Hughes, T. (1987). The evolution of large technological systems. In W. Bijker, T. Hughes, & T. Pinch (Eds.), *The social construction of large technological systems.* Massachusetts: Massachusetts Institute of Technology.

Hülsbergen, K.-J., & Küstermann, B. (2007). Ökologischer Landbau - Beitrag zum Klimaschutz. In K. Wiesinger (Ed.), *Angewandte Forschung und Beratung für den ökologischen Landbau in Bayern* (pp. 9-21): Bayerische Landesanstalt für Landwirtschaft.

Hunter, D., Salzman, J., & Zaelke, D. (2015). *International Environmental Law and Policy, Revised 5th Edition.* Foundation Press.

Hutchins, M., & Sutherland, J. (2008). An exploration of measures of social sustainability and their application to supply chain decisions. *Journal of Cleaner Production, 16*(15), 1688-1698.

Huth, p. K. (1998). *Standing Your Ground: Territorial Disputes and International Conflict*: The University of Michigan Press.

ICLEI – Local Governments for Sustainability, UN_HABITAT, & UN Environment. (2009). *Sustainable Urban Energy Planning. A handbook for cities and towns in developing countries.* Available from: http://www.unep.org/urban_environment/PDFs/Sustainable_Energy_Handbook.pdf

ICN2. (2014). *Rome Declaration on Nutrition. Second International Conference on Nutrition.* Rome: WHO and FAO.

IDB. (2015). *Inter-American Development Bank (IDB) Energy Sector Framework Document, November 2015.* Available from: http://idbdocs.iadb.org/wsdocs/getdocument.aspx?docnum=40018070

IEA. (2008). *Energy Technology Perspectives: Scenarios & Strategies to 2050.* Paris, France: International Energy Agency.

IEA. (2009). *Transport, energy and CO_2 - moving toward sustainability.* Paris, France: IEA.

IEA. (2010a). *Energy Efficiency Governance.* Available from: https://www.iea.org/publications/freepublications/publication/eeg.pdf

IEA. (2010b). *Energy Efficiency Governance Handbook.* Available from: http://www.iea.org/publications/freepublications/publication/gov_handbook.pdf

IEA. (2010c). *Energy Technology Perspectives 2010 - scenarios and strategies to 2050.* Paris, France: IEA.

IEA. (2011). *IEA Scoreboard 2011. Implementing energy efficiency* *policy: progress and challenges in IEA member countries. ISBN 978-92-64-12459-2.* Available from: https://www.iea.org/publications/freepublications/publication/iea-scoreboard-2011.html

IEA. (2012a). *Energy Technology Perspectives 2012 - pathways to a clean energy system.* Paris, France: IEA.

IEA. (2012b). *World Energy Outlook.* Paris, France: IEA.

IEA. (2013a). *Energy policies of IEA countries - 2013 Germany review.* Paris, France: IEA.

IEA. (2013b). Statistics. Available from: http://www.iea.org/statistics/statisticssearch/

IEA. (2015). *2015 Key World Energy Statistics.* Available from: https://www.iea.org/publications/freepublications/publication/KeyWorld_Statistics_2015.pdf

IFA. (2009). *Energy Efficiency and CO_2 Emissions in Ammonia Production 2008-2009 Summary Report.* Paris, France: IEA.

IFAD. (2011). *International Fund for Agricultural Development (IFAD). Rural Poverty Report 2011.* Rome: IFAD.

IIASA. (2015). *SSP Scenario Database.* Available from: http://www.iiasa.ac.at/web/home/research/researchPrograms/Energy/SSP_Scenario_Database.html

IISD. (1994). OECD – MIT Experts Seminar on Sustainable Consumption and Production Patterns. Available from: http://www.iisd.ca/consume/mit.html

IISD. (1995). Oslo Roundtable on Sustainable Production and Consumption. Available from: www.iisd.ca/consume/oslo004.html

INFONAVIT. (2013). *Informe anual de la sustenabilidad 2012.* Cambridge, United Kingdom: Cambridge University Press.

IPCC. (2014a). *Climate Change 2014. Synthesis Report - Summary for Policymakers.* Cambridge, United Kingdom: Cambridge University Press.

IPCC. (2014b). *Climate Change 2014: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, United Kingdom: Cambridge University Press.

IPCC. (2014c). *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, United Kingdom: Cambridge University Press.

IPCC. (2014d). Summary for policymakers. In O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, p. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, & J. C. Minx (Eds.), *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, United Kingdom: Cambridge University Press.

ITU. (2015). *International Telecommunication Union Yearbook of Statistics.* Available from: http://www.itu.int

IUCN. (2014). *International Union for Conservation of Nature Annual Report 2014.* Geneva: IUCN

Jackson, T. (2009). *Prosperity without growth – economics for a finite planet.* London: Earthscan.

Jacobsen, N. (2006). Industrial Symbiosis in Kalundborg, Denmark: A Quantitative Assessment of Economic and Environmental Aspects. *Journal of Industrial Ecology, 10*(1-2), 239-255.

Jayanetti, L., & Follet, p. (2003). Bamboo in construction: status and potential. In S. Edwards & p. Bennet (Eds.), *Construction products and life-cycle thinking* (pp. 64-65).

Jin, Y., Kim, J., & Guillaume, B. (2016). Review of critical material studies. *Resources, Conservation and Recycling, 113*, 77-87.

Jones, C., & Kammen, D. M. (2014). Spatial Distribution of US Household Carbon Footprints Reveals Suburbanization Undermines Greenhouse Gas Benefits of Urban Population Density. *Environmental Science & Technology, 48*(2), 895-902.

JRC. (2015). *Best environmental management practice for the agricultural sector - crop and animal production.* Sevilla: Joint Research Centre Institute for Prospective Technological Studies.

Jung, K., & Hwang, H. (2011). Competition and cooperation in a remanufacturing system with take-back requirement. *Journal of Intelligent Manufacturing, 22*(3_supplement), 427-433.

Kagawa, S., Kudoh, Y., Nansai, K., & Tasaki, T. (2008). The Economic and Environmental Consequences of Automobile Lifetime Extension and Fuel Economy Improvement: Japan's Case. *Economic Systems Research, 20*(1), 3-28.

Kaplinsky, R., & Morris, M. (2001). *A Handbook for Value Chain Research.* Ottawa: International Development Research Centre.

Kear, G., & Chapman, R. (2013). 'Reserving judgement': Perceptions of pumped hydro and utility-scale batteries for electricity storage and reserve generation in New Zealand. *Renewable Energy, 57*, 249-261.

Kennedy, C., Steinberger, J., Gasson, B., Hansen, Y., Hillman, T., Havránek, M., ... Mendez, G. (2009). Greenhouse Gas Emissions from Global Cities. *Environmental Science & Technology, 43*(19), 7297-7302.

Kennedy, C., Stewart, I., Facchini, A., Cersosimo, I., Mele, R., Chen, B., ... Sahin, A. (2015). Energy and material flows of megacities. *Proceedings of the National Academy of Sciences of the United States of America, 112*(19), 5985-5990.

Kharas, H. (2010). *The emerging middle class in developing countries. OECD Development Centre, Working Paper No.285.*

Kharina, A., & Rutherford, D. (2015). *Fuel efficiency trends for new commercial jet aircraft: 1960 to 2014.* Washington, D.C.: The International Council on Clean Transportation.

Khetriwal, D., & First, I. (2012). Enabling closed resource loops in electronics: understanding consumer disposal behaviour using insights from diffusion models. *Ekonomska Istrazivanja, 25*(supplement), 47-68.

Kim, R. E. (2013). The emergent network structure of the multilateral environmental agreement system. *Global Environmental Change, 23*(5), 980-991.

Kleijn, R., & van der Voet, E. (2010). Resource constraints in a hydrogen economy based on renewable energy sources: An exploration. *Renewable and Sustainable Energy Reviews, 14*(9), 2784-2795.

Kliot, N., Shmueli, D., & Shamir, U. (2001). Institutions for management of transboundary water resources: their nature, characteristics and shortcomings. *Water Policy, 3*, 229–255.

Kochhar, K., Pattillo, C., Sun, Y., Suphaphiphat, N., Swiston, A., Tchaidze, R., ... Finger, H. (2015). *Is the glass half empty of half full? Issues in managing water challenges and policy instruments. Available* from: http://www.imf.org/external/pubs/ft/sdn/2015/sdn1511.pdf

Kolstad, I., & Søreide, T. (2009). Corruption in natural resource management: Implications for policy makers. *Resources Policy, 34*, 214–226.

Kolstad, I., & Wiig, A. (2009). Is Transparency the Key to Reducing Corruption in Resource-Rich Countries? *World Development, 37*(3), 521–532.

Koornneef, J., Ramirez, A., Turkenburg, W., Ramírez, A., & Faaij, A. (2012). The environmental impact and risk assessment of CO_2 capture, transport and storage – An evaluation of the knowledge base. *Progress in energy and combustion science, 38*(1), 62-86.

Kowalski, P., Büge, M., Sztajerowska, M., & Egeland, M. (2013). *State-Owned Enterprises: Trade Effects and Policy Implications. OECD Trade Policy Papers No. 147*, 2013.

Krausmann, F., Erb, K.-H., Gingrich, S., Haberl, H., Bondeau, A., Gaube, V., ... Searchinger, T. D. (2013). Global human appropriation of net primary production doubled in the 20th century. *Proceedings of the National Academy of Sciences, 110*(25), 10324-10329.

Krausmann, F., Gaugl, B., West, J., & Schandl, H. (2016). The metabolic transition of a planned economy: Material flows in the USSR and the Russian Federation 1900 to 2010. *Ecological Economics, 124*, 76-85.

Krausmann, F., Gingrich, S., Eisenmenger, N., Erb, K.-H., Haberl, H., & Fischer-Kowalski, M. (2009). Growth in global materials use, GDP and population during the 20th century. *Ecological Economics, 68*(10), 2696-2705.

Kromarek, p. (1990). Environmental Protection and Free Movement of Goods: the Danish Bottles Case: Commission of the European Communities (supported by United Kingdom) v Kingdom of Denmark (European Court of Justice, Lord Mackenzie Stuart, President, G. Bosco, O. Due,J. C. Moitinho de Almeida and G. C. Rodriguez Inglesias (Presidents of Chambers), U. Everling, K. Bahlmann, Y. Galmot, C. N. Kakouris, R.Joliet and F. A. Schockweiler, Judges, 20 September 1988). *Journal of Environmental Law, 2*(1), 89-107.

Kumar, A., Schei, T., Ahenkorah, A., Rodriguez, R. C., Devernay, J.-M., Freitas, M., ... Liu, Z. (2011). Hydropower. In O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, p. Matschoss, S. Kadner, T. Zwickel, p. Eickemeier, G. Hansen, S. Schlömer, & C. v. Stechow (Eds.), *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*. Cambridge, UK / New York, NY, USA: Cambridge University Press.

Kumar, D., & Katoch, S. S. (2016). Environmental sustainability of run of the river hydropower projects: A study from western Himalayan region of India. *Renewable Energy, 93*, 599-607.

Kumar, p. (Ed.) (2012). *The economics of ecosystems and biodiversity: ecological and economic foundations*. Oxford, New York: Routledge Press.

Kurian, M. (2016). The water-energy-food nexus: Trade-offs, thresholds and transdisciplinary approaches to sustainable development. *Environmental Science & Policy.*

Kurian, M., & Ardakanian, R. (Eds.). (2015). *Governing the Nexus: Water, Soils and Waste Resources Considering Global Change.* UNU/Springer.

Langevin, J., Gurian, P., & Wen, J. (2013). Reducing energy consumption in low income public housing: Interviewing residents about energy behaviors. *Applied energy, 102*, 1358-1370.

Langholtz, M. H., Coleman, A. M., Eaton, L. M., Wigmosta, M. S., Hellwinckel, C. M., & Brandt, C. C. (2016). Potential land competition between open-pond microalgae production and terrestrial dedicated feedstock supply systems in the US *Renewable Energy, 93*, 201-214.

Laurenti, R., Sinha, R., Singh, J., & Frostell, B. (2015). Some pervasive challenges to sustainability by design of electronic products – a conceptual discussion. *Journal of Cleaner Production, 108, Part A*, 281-288.

Layard, R. (2005). *Happiness: Lessons from a New Science.* London: Penguin.

Lee, J. S. H., Jaafar, Z., Tan, A. K. J., Carrasco, L. R., Ewing, J. J., Bickford, D. P., ... Koh, L. p. (2016). Toward clearer skies: Challenges in regulating transboundary haze in Southeast Asia. *Environmental Science & Policy, 55, Part 1*, 87-95.

Leite, C., & Weidmann, J. (1999). *Does Mother Nature Corrupt? Natural Resources, Corruption and Economic Growth. International Monetary Fund Working Paper WP/99/85.*

Lenzen, M., Moran, D., Kanemoto, K., & Geschke, A. (2013). Building eora: a global multi-region input–output database at high country and sector resolution. *Economic Systems Research, 25*(1), 20-49.

Levy, D. L., & Newell, p. J. (2004). *The Business of Global Environmental Governance:* MIT Press.

LG Action. (n.d.). Ljubljana, Slovenia. Energy improvements in social housing. Brief case study on local climate and energy actions.

Lim, B., & Spanger-Siegfried, E. (Eds.). (2004). *Adaptation Policy Frameworks for Climate Change: Developing Strategies, Policies and Measures*. New York: UNDP/CUP.

Lindau, L., Hidalgo, D., & Facchini, D. (2010). Bus Rapid Transit in Curitiba, Brazil. *Transportation research record, 2193*(2193), 17-27.

Liu, Q., Lu, R., & Ma, X. (2015). Corruption, Financial Resources and Exports. *Review of International Economics, 23*(5), 1023-1043.

Lombardi, D. R., & Laybourn, p. (2012). Redefining Industrial Symbiosis. *Journal of Industrial Ecology, 16*(1), 28-37.

Lovett, A. A., Dockerty, T. L., Papathanasopoulou, E., Beaumont, N. J., & Smith, p. (2015). A framework for assessing the impacts on ecosystem services of energy provision in the UK: An example relating to the production and combustion life cycle of UK produced biomass crops (short rotation coppice and Miscanthus). *Biomass & bioenergy, 83*, 311-321.

Land Transport Authority (LTA). (2011). *Passenger Transport Mode Shares in World Cities.* Available from: http://www.lta.gov.sg/ltaacademy/doc/J14Nov_p54ReferenceModeShares.pdf

Lutz, C., & Lehr, U. (2015). Macroeconomic effects of renewable energy and energy efficiency policies with a focus on Germany. In L. Bernard & W. Semmler (Eds.), *The Oxford Handbook of the Macroeconomics of Global Warming* (pp. 477-496). Oxford: Oxford University Press.

Ma, L., Ma, W. Q., Velthof, G. L., Wang, F. H., Qin, W., Zhang, F. S., & Oenema, O. (2010). Modeling Nutrient Flows in the Food Chain of China. *Journal of Environmental Quality, 39*(4), 1279-1289.

Mace, G. M., Hails, R. S., Cryle, P., Harlow, J., & Clarke, S. J. (2015). REVIEW: Towards a risk register for natural capital. *Journal of Applied Ecology, 52*(3), 641-653.

Maheshwari, B. (2006). *The efficiency and audit of residential irrigation systems in the Sydney Metropolitan Area.* Queensland, Australia: The International Council on Clean Transportation.

Majule, A., Stathers, T., Lamboll, R., Liwenga, E. T., & Kallanda-Sabola, M. (2011). *Exploring opportunities for enhancing capacities to individuals, institutions and political domains to adapt to climate change in agricultural sector: A case of Tanzania and Malawi.* Paper presented at the Africa Adapt Climate Change Symposium, Panel 16: Special Panel on Innovations in Agriculture and Food Security.

Martín, M., & Grossmann, I. E. (2015). Water–energy nexus in biofuels production and renewable based power. *Sustainable Production and Consumption, 2*, 96-108.

Matsumoto, M., Yang, S., Martinsen, K., & Kainuma, Y. (2016). Trends and research challenges in remanufacturing. *International Journal of Precision Engineering and Manufacturing - Green Technology, 3*(1), 129-142.

McCready, M. S., Dukes, M. D., & Miller, G. L. (2009). Water conservation potential of smart irrigation controllers on St. Augustinegrass. *Agricultural Water Management, 96* (11), 1623-1632.

McGlade, C., & Ekins, p. (2015). The geographical distribution of fossil fuels unused when limiting global warming to 2 [deg]C. *Nature, 517*(7533), 187-190.

McGraw-Hill Construction. (2013). *World Green Building Trends. Business Benefits Driving New and Retrofit Market Opportunities in Over 60 Countries.* Available from: http://www.worldgbc.org/sites/default/files/World_Green_Building_Trends_SmartMarket_Report_2013.pdf

McHarg, A., Barton, B., Bradbrook, A., & Golden, L. (2010). *Property and the Law in Energy and Natural Resources*. Oxford: Oxford University Press.

McKenna, R., Reith, S., Cail, S., Kessler, A., & Fichtner, W. (2013). Energy savings through direct secondary reuse: an exemplary analysis of the German automotive sector. *Journal of Cleaner Production, 52*, 103-112.

MEA. (2005). *Millennium Ecosystem Assessment (2005). Ecosystems and Human Well-being: Synthesis.* Washington, DC.: Island Press.

Meehan, J., & Bryde, D. (2011). Sustainable procurement practice. *Business Strategy and the Environment, 20*(2), 94-106.

Melissen, F., & Reinders, H. (2012). A reflection on the Dutch Sustainable Public Procurement Programme. *Journal of integrative environmental sciences, 9*(1), 27-36.

Meyer, B., Distelkamp, M., & Beringer, T. (2015). *Report about integrated scenario interpretation: GINFORS/LPJml results. Deliverable D3.7a for the FP7 project POLFREE (Policy Options for a Resource-Efficient Economy).* Available from: http://www.polfree.eu/publications/publications-2014/integrated-scenario-interpretation

McKinsey Global Institute. (2011). *Urban World: mapping the economic power of cities.*

Milligan, B. (2012). *Legal and policy options for the provisional joint management of maritime spaces subject to overlapping jurisdictional claims.* University of Wollongong. Available from: http://ro.uow.edu.au/theses/3782

Milligan, B., Terama, E., Jimenez–Aybar, R., & Ekins, p. (2014). GLOBE Natural Capital Accounting Study, 2nd Edition. GLOBE International and University College London.

Mills, B., & Schleich, J. (2010). What's driving energy efficient appliance label awareness and purchase propensity? *Energy Policy, 38*(2), 814-825.

Ministry of the Environment. (2003). *Fundamental Plan for Establishing a Sound Material-Cycle Society*. Available from: http://www.env.go.jp/en/recycle/smcs/f_plan.pdf

Ministry of the Environment. (2005). *Japan's experience in promotion of the 3Rs for the establishment of a sound material-cycle society*. Available from: http://www.env.go.jp/recycle/3r/en/approach/02.pdf

Miranda, L. A. (2012). The Role of International Law in Intrastate Natural Resources Allocation: Sovereignty, Human Rights, and People-Based Development. *Vanderbilt Journal of Transnational Law, 45*, 785–840.

Mitchell, L. (2013). *Natural Resource Contracts: A Practical Guide.* Environmental Law Alliance Worldwide (ELAW).

Miyoshi, C., & Givoni, M. (2013). The Environmental Case for the High-Speed Train in the UK: Examining the London–Manchester Route. *International journal of sustainable transportation, 8*(2), 107-126.

Molenbroek, E., Smith, M., Groenenberg, H., Waide, P., Attali, S., Fischer, c., ... Fong, J. (2014). *Evaluation of the Energy Labelling Directive and specific aspects of the Ecodesign Directive. Final Technical Report.* Available from: http://www.energylabelevaluation.eu/tmce/Final_technical_report-Evaluation_ELD_ED_June_2014.pdf

Monteith, J. L. (1990). Can sustainability be quantified? *Indian J. Dryland Agric. Res. and Dev., 5* (1-2), 1-15.

Moomaw, W., Griffin, T., Kurczak, K., & Lomax, J. (2012). *The Critical Role of Global Food Consumption Patterns in Achieving Sustainable Food Systems and Food for All, A UNEP Discussion Paper.* Paris, France: UN Environment.

Moriguchi, Y. (2007). Material flow indicators to measure progress toward a sound material-cycle society. *Journal of Material Cycles and Waste Management, 9*(2), 112-120.

Moroz, J. G., Lissel, S. L., & Hagel, M. D. (2014). Performance of bamboo reinforced concrete masonry shear walls. *Construction and Building Materials, 61*, 125-137.

Morrison, J., & Roht-Arriaza, N. (2007). Private and Quasi-Private Standard Setting. In D. Bodansky, J. Brunnée, & E. Hey (Eds.), *The Oxford Handbook of International Environmental Law*. Oxford: Oxford University Press.

Moynihan, M., & Allwood, J. (2014). Utilization of structural steel in buildings. *Proceedings - Royal Society. Mathematical, physical and engineering sciences, 470*(2168), 20140170-20140170.

Msangi, S., & Rosegrant, M. (2009). *World agriculture in a dynamically-changing environment: IFPRI's long-term outlook for food and agriculture under additional demand constraints.* Paper presented at the FAO Expert Meeting, 24-26 June 2009, on "How to Feed the World in 2050". Rome: FAO.

Mueller, N. D., Gerber, J. S., Johnston, M., Ray, D. K., Ramankutty, N., & Foley, J. A. (2012). Closing yield gaps through nutrient and water management. *Nature, 490*(7419), 254-257.

Muller, D., Liu, G., Lovik, A., Modaresi, R., Pauliuk, S., Müller, D., ... Brattebø, H. (2013). Carbon Emissions of Infrastructure Development. *Environmental Science & Technology, 47*(20), 11739-11746.

Mwandosya, M., & Namiki, M. (2008). *Conclusions by the conference co-chairs.* Paper presented at the Conference on resource efficiency. 23rd April, 2008, Paris, France.

Nahlik, M. J., Kaehr, A. T., Chester, M. V., Horvath, A., & Taptich, M. N. (2016). Goods Movement Life Cycle Assessment for Greenhouse Gas Reduction Goals. *Journal of Industrial Ecology, 20*(2), 317-328.

Nasr, N. (2010). Reman for success. *Industrial engineer, 42*(6), 26-26.

National Resources Canada. (2015). *Four Centres at Red Deer College.* Available from: http://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/oee/files/pdf/publications/commercial/Red_Deer_Case-Study_access_e.pdf

NCE. (2014). *Better Growth Better Climate: The New Climate Economy Report, The Global Report, September*. Available from: http://2014.newclimateeconomy.report/

Neate, p. (2013). *Climate-smart agriculture success stories from farming communities around the world*. Wageningen, Netherlands: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) and the Technical Centre for Agricultural and Rural Cooperation (CTA).

Neumann, K., Verburg, P., Stehfest, E., Mueller, C., & Müller, C. (2010). The yield gap of global grain production: A spatial analysis. *Agricultural systems, 103*(5), 316-326.

Newig, J., & Fritsch, O. (2009). Environmental Governance: Participatory, Multi-level – and Effective? *Environmental Policy and Governance, 19*, 197–214.

Newman, p. W. G., & Kenworthy, J. (1989). Gasoline Consumption and Cities. *American Planning Association. Journal of the American Planning Association, 55*(1), 24-37.

Ng, M., Fleming, T., Robinson, M., Thomson, B., Graetz, N., Margono, C., ... Gakidou, E. (2014). Global, regional, and national prevalence of overweight and obesity in children and adults during 1980–2013: a systematic analysis for the Global Burden of Disease Study 2013. *The Lancet, 384*(9945), 766-781.

Nguyen, B., & Altan, H. (2011). Comparative Review of Five Sustainable Rating Systems. *Procedia Engineering, 21*, 376-386.

Nikolaeva, R., & Bicho, M. (2011). The role of institutional and reputational factors in the voluntary adoption of corporate social responsibility reporting standards. *Journal of the Academy of Marketing Science, 39*(1), 136–157.

NISP. (2009). *The Pathway to a Low Carbon Sustainable Economy.* Birmingham: National Industrial Symbiosis Programme, International Synergies.

Nordhaus, W. (2010). Economic aspects of global warming in a post-Copenhagen environment. *Proceedings of the National Academy of Sciences of the United States of America, 107*(26), 11721-11726.

Northey, S., Mohr, S., Mudd, G. M., Weng, Z., & Giurco, D. (2014). Modelling future copper ore grade decline based on a detailed assessment of copper resources and mining. *Resources, conservation, and recycling, 83*, 190-201.

NRC. (2009). *Driving and the Built Environment: The Effects of Compact Development on Motorized Travel, Energy Use, and CO_2 Emissions.* National Research Council Committee for the Study on the Relationships Among Development Patterns, Vehicle Miles Traveled, and Energy Consumption.

NRGI. (2014). *Natural Resource Charter, 2nd Edition*. New York: Natural Resource Governance Institute.

Nunes, J., Silva, p. D., Andrade, L. P., & Gaspar, p. D. (2016). Key points on the energy sustainable development of the food industry – Case study of the Portuguese sausages industry. *Renewable and Sustainable Energy Reviews, 57*, 393-411.

O'Brien, M., & Miedzinski, M. (Eds.). (2012). *Closing the eco-innovation gap - an economic opportunity for business. Annual report 2011*. Brussels: Eco-innovation observatory, European Commission.

O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., ... Solecki, W. (2015). The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change.*

OECD. (2001). *Extended Producer Responsibility: A Guidance Manual for Governments.* Paris, France: OECD.

OECD. (2002). *Measuring material flows and resource productivity. Volume 1. The OECD Guide Glossary.* Paris, France: OECD.

OECD. (2006). *The Challenge of Capacity Development: Working Towards Good Practice. DAC Guidelines and Reference Series.* Paris, France: OECD.

OECD. (2008a). Measuring material flows and resource productivity - Volume I. Paris, France: OECD

OECD. (2008b). Resource Productivity in the G8 and the OECD: A Report in the Framework of the Kobe 3R Action Plan. Paris, France: OECD.

OECD. (2009). *Managing water for all - an OECD perspective on pricing and financing.* Available from: http://www.oecd.org/tad/sustainable-agriculture/44476961.pdf

OECD. (2011). *Resource Productivity in the G8 and the OECD - A Report in the Framework of the Kobe 3R Action Plan*. Available from: https://www.oecd.org/env/waste/47944428.pdf

OECD. (2012a). *Green Growth and Developing Countries: Consultation Draft.* Available from: http://www.oecd.org/environment/environment-development/50559116.pdf

OECD. (2012b). *OECD Environmental Outlook to 2050.* Paris, France: OECD.

OECD. (2013a). *Issues Paper on Corruption and Economic Growth. G20 Leaders Summit, St Petersburg, September 2013.* Available from: http://www.oecd.org/g20/topics/anti-corruption/Issue-Paper-Corruption-and-Economic-Growth.pdf

OECD. (2013b). *Water Security for Better Lives. OECD studies on water.* Paris, France: OECD.

OECD. (2014a). *OECD Obesity Update 2014*. Paris, France: OECD.

OECD. (2014b). Smart Procurement. Going green: best practices for green procurement. Available from: http://www.oecd.org/gov/ethics/best-practices-for-green-procurement.htm

OECD. (2015a). *The Economic Consequences of Climate Change*. Paris, France: OECD.

OECD. (2015b). *Material resources, productivity and the environment*. Paris, France: OECD.

OECD. (2015c). *Policy Framework for Investment - 2015 Edition*. Paris, France: OECD.

OECD. (2016). *Policy Guidance on Resource Efficiency*. Available from: http://www.oecd.org/env/policy-guidance-on-resource-efficiency-9789264257344-en.htm

OECD, & FAO. (2014). *Agricultural Outlook 2014-2023*. Available from: http://www.oecd-ilibrary.org/agriculture-and-food/oecd-fao-agricultural-outlook-2014_agr_outlook-2014-en

OECD, World Bank, & UN. (2012). *Incorporating Green Growth and Sustainable Development Policies into Structural Reform Agendas. Report prepared for the G20 Summit, Los Cabos, 18–19 June 2012.* Available from: http://www.oecd.org/g20/topics/energy-environment-green-growth/G20_report_on_GG_and_SD_final.pdf

OECD, WTO, & World Bank. (2014). *Global Value Chains: Challenges, Opportunities, and Implications for Policy.*

OICA. (2016). International organisation of motor vehicle manufacturers. Available from: http://www.oica.net/world-vehicles-in-use-all-vehicles-2/

Osamu, K. (2012). The role of standards: the Japanese Top Runner Program for end-use efficiency. Historical case studies of energy technology innovation. In Grubler A. , F. Aguayo, K. S. Gallagher, M. Hekkert, K. Jiang, L. Mytelka, L. Neij, G. Nemet, C. Wilson, & (Eds.). Cambridge, UK.: Cambridge University Press.

Palmer, D. (2012). Improving the Governance of Tenure of Land, Fisheries and Forests. *FAO Land Tenure Journal, 1.*

Park, J. M., Park, J. Y., & Park, H.-S. (2016). A review of the National Eco-Industrial Park Development Program in Korea: progress and achievements in the first phase, 2005–2010. *Journal of Cleaner Production, 114*, 33-44.

Parto, S., Loorbach, D., Lansink, A., & Kemp, R. (2007). Transitions and institutional change: the case of the Dutch waste subsystem. In S. Parto & B. Herbert-Copley (Eds.), *Industrial innovation and environmental regulation: developing workable solutions*. Tokyo: United Nations University Press.

Pattberg, p. (2005). What Role for Private Rule-Making in Global Environmental Governance? Analysing the Forest Stewardship Council (FSC). *International Environmental Agreements, 5*, 175–189.

Pattberg, p. (2007). Private Institutions and Global Governance: *The New Politics of Environmental Sustainability*: Edward Elgar.

PBL. (2012). *Roads from Rio+20*. The Hague: Netherlands Environmental Assessment Agency.

PBL. (2014a). How sectors can contribute to sustainable use and conservation of biodiversity The Hague: PBL & CBD.

PBL. (2014b). *Sustainability of international Dutch supply chains. Progress, effects and perspectives.* The Hague: Netherlands Environmental Assessment Agency.

Perera, O. (2012). *The Case for Pursuing Sustainable Public Procurement in Lower Income Countries. International Institute for Sustainable Development Commentary September 2012.* International Institute for Sustainable Development.

Persson, U., Marcelino, R., Victoria, M., Gabriel, A., Daniel, B., & Landin, A. (2008). *Ten Years Of Sustainable Construction Aspects From A North And A South Perspective–A Review From Sustainable Building Conferences 1998-2007*. Paper presented at the World Sustainable Building Conference, SB08.

Pess, G. R., McHenry, M. L., Beechie, T. J., & Davies, J. (2008). Biological Impacts of the Elwha River Dams and Potential Salmonid Responses to Dam Removal. *Northwest Science, 82*(sp1), 72-90.

Peters, G. P., & Hertwich, E. G. (2008). CO_2 Embodied in International Trade with Implications for Global Climate Policy. *Environmental Science & Technology, 42*(5), 1401-1407.

Phalan, B., Green, R., & Balmford, A. (2014). Closing yield gaps: perils and possibilities for biodiversity conservation. *Philosophical Transactions of the Royal Society of London B: Biological Sciences, 369*(1639).

PIU. (2001). *Resource productivity: making more with less*. London: PIU.

Ponisio, L. C., M'Gonigle, L. K., Mace, K. C., Palomino, J., de Valpine, P., & Kremen, C. (2014). Diversification practices reduce organic to conventional yield gap. *Proceedings of the Royal Society of London B: Biological Sciences, 282*(1799).

Porter, W. C., Rosenstiel, T. N., Guenther, A., Lamarque, J.-F., & Barsanti, K. (2015). Reducing the negative human-health impacts of bioenergy crop emissions through region-specific crop selection. *Environmental Research Letters, 10*(5), 054004.

Poschen, p. (2015). *Decent Work, Green Jobs and the Sustainable Economy, International Labour Office, Geneva.* Sheffield: Greenleaf Publishing.

PPPIRC. (2016). China Circular Economy Promotion Law. Available from: https://ppp.worldbank.org/public-private-partnership/library/china-circular-economy-promotion-law

Prescott, V., & Schofield, C. (2004). *The Maritime Political Boundaries of the World, 2nd Edition*: Brill | Nijhoff.

Pretty, J., Toulmin, C., & Williams, S. (2011). Sustainable intensification in African agriculture. *International Journal of Agricultural Sustainability, 9*(1), 5-24.

PWC. (2015). *The Sharing Economy*. Available from: www.pwc.com/us/en/technology/publications/assets/pwc-consumer-intelligence-series-the-sharing-economy.pdf

Querol, A. A., & Schaefer, B. (2013). *SEAD Guide for Monitoring and Evaluating Green Public Procurement Programs*. Barcelona: Ecoinstitut.

Quested, T. E., Marsh, E., Stunell, D., & Parry, A. D. (2013). Spaghetti soup: The complex world of food waste behaviours. *Resources, Conservation and Recycling, 79*, 43-51.

Rabbitt, N., & Ghosh, B. (2013). A study of feasibility and potential benefits of organised car sharing in Ireland. *Transportation Research Part D: Transport and Environment, 25*, 49-58.

Rabotyagov, S. S., Kling, C. L., Gassman, p. W., Rabalais, N. N., & Turner, R. E. (2014). The Economics of Dead Zones: Causes, Impacts, Policy Challenges, and a Model of the Gulf of Mexico Hypoxic Zone. *Review of environmental economics and policy, 8*(1), 58-79.

Rainforest Alliance. (2010). *The Costs and Benefits of Implementing Best Management Practices for Tourism Businesses*. Available from: http://www.rainforest-alliance.org/sites/default/files/publication/pdf/cost_benefits_tourism_best_practices.pdf

Rainforest Alliance. (2013). *International Alliance for the Marketing and Commercialization of Sustainable Tourism Services: Executive Summary*. Available from: http://www.rainforest-alliance.org/publications/alliance-marketing-sustainable-tourism-summary

Ramaswami, A., Bernard, M., Chavez, A., Hillman, T., Whitaker, M., Thomas, G., & Marshall, M. (2012). Quantifying Carbon Mitigation Wedges in US Cities: Near-Term Strategy Analysis and Critical Review. *Environmental Science & Technology, 46*(7), 3629-3642.

Ramaswami, A., Jiang, D., Tong, K., & Zhao, J. Z. (2016). Economic Structure of Cities and Urban Scaling Factors: Implications for Urban Material-Energy Flows in China. *Journal of Industrial Ecology, In review.*

Ramaswami, A., Weible, C., Main, D., Heikkila, T., Siddiki, S., Duvall, A., ... Bernard, M. (2012). A Social-Ecological-Infrastructural Systems Framework for Interdisciplinary Study of Sustainable City Systems. *Journal of Industrial Ecology, 16*(6), 801-813.

Raptis, C. E., & Pfister, S. (2016). Global freshwater thermal emissions from steam-electric power plants with once-through cooling systems. *Energy, 97*, 46-57.

Rasul, G. (2012). *Contribution of Himalayan Ecosystems to Water, Energy, and Food Security in South Asia: a nexus approach.* Kathmandu: International Centre for Integrated Mountain Development.

Reardon, T., & Timmer, C. p. (2012). The Economics of the Food System Revolution. *Annual review of resource economics, 4*(1), 225-264.

REBus. (2016). REBus Home Page. Available from: http://www.rebus.eu.com/

Reconnecting America. (2007). *Why transit-oriented development and why now.* Available from: http://www.reconnectingamerica.org/resource-center/browse-research/2007/tod-101-why-transit-oriented-development-and-why-now/

Reczkova, L., Sulaiman, J., & Bahari, Z. (2013). Some Issues of Consumer Preferences for Eco-labeled Fish to Promote Sustainable Marine Capture Fisheries in Peninsular Malaysia. *Procedia - Social and Behavioral Sciences, 91*, 497-504.

Reeve Consulting. (2014). *The Annual Report on the State of Municipal Sustainable Procurement in Canada. Trends & Best Practices.* Municipal Collaboration for Sustainable Procurement January 2014.

Rehman, S., Al-Hadhrami, L. M., & Alam, M. M. (2015). Pumped hydro energy storage system: A technological review. *Renewable and Sustainable Energy Reviews, 44*, 586-598.

Rejwan, A. (2011). *The State of Israel: national water efficiency report.* Available from: http://www.water.gov.il/Hebrew/ProfessionalInfoAndData/2012/24-The-State-of-Israel-National-Water-Efficiency-Report.pdf

Renne, J. L., Tolford, T., Hamidi, S., & Ewing, R. (2016). The Cost and Affordability Paradox of Transit-Oriented Development: A Comparison of Housing and Transportation Costs Across Transit-Oriented Development, Hybrid and Transit-Adjacent Development Station Typologies. *Housing Policy Debate, 26*(4-5), 819-834.

Renner, M. (2013). Air transport keeps expanding.

Reuter, M., & van Schaik, A. (2012). Opportunities and limits of recycling: A dynamic-model-based analysis. *MRS Bulletin, 37*(04), 339-347.

Reymond, P., Cofie, O., Raschid, L., & Kone, D. (2009). *SWITCH Project Report, Design Considerations and Constraints in Applying Onfarm Wastewater Treatment for Urban Agriculture.*

Ribeiro, F. d. M., & Kruglianskas, I. (2013). Improving environmental permitting through performance-based regulation: a case study of Sao Paulo State, Brazil. *Journal of Cleaner Production, 46*, 15-26.

Ringler, C., Bhaduri, A., & Law, R. (2013). The nexus across water, energy, land and food (WELF): potential for improved resource use efficiency? *Current Opinion in Environmental Sustainability, 5*, 617–624.

Robbins, p. (2000). The rotten institution: corruption in natural resource management. *Political Geography, 19*(4), 423–443.

Rockström, J., Steffen, W., Noone, K., Persson, A., Chapin, F. S., Lambin, E. F., ... Foley, J. A. (2009). A safe operating space for humanity. *Nature, 461*(7263), 472-475.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S. I., Lambin, E., ... Foley, J. (2009). Planetary boundaries: exploring the safe operating space for humanity. *Ecology and Society, 14*(2).

Roeder, M., Whittaker, C., Thornley, P., & Röder, M. (2015). How certain are greenhouse gas reductions from bioenergy? Life cycle assessment and uncertainty analysis of wood pellet-to-electricity supply chains from forest residues. *Biomass & bioenergy, 79*, 50-63.

Rogelj, J., Meinshausen, M., & Knutti, R. (2012). Global warming under old and new scenarios using IPCC climate sensitivity range estimates. *Nature Climate Change, 2*(4), 248-253.

Rogner, H.-H., Aguilera, R. F., Archer, C., Bertani, R., Bhattacharya, S. C., Dusseault, M. B., ... Yakushev, V. (2012). Chapter 7 - Energy Resources and Potentials *Global Energy Assessment - Toward a Sustainable Future* (pp. 423-512). Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria.

Rose, G., & Milligan, B. (2009). Law for the Management of Antarctic Marine Living Resources: From Normative Conflicts towards Integrated Governance? *Yearbook of International Environmental Law, 20*(1), 41–87.

Rothwell, D. (1996). *The Polar Regions and the Development of International Law.* Cambridge: Cambridge University Press.

RRI. (2015). *Who Owns the World's Land? A Global Baseline of Formally Recognized Indigenous and Community Land Rights*. Rights and Resources Initiative.

RRI. (2016). Closing the Gap: Strategies and scale needed to secure rights and save forests. *Rights and Resources Initiative Annual Review 2015–2016*.

Ruhl, J. B., Kraft, S., & Lant, C. (2007). Washington, D.C.: Island Press.

Russell, D., & Vanderzwaag, D. (Eds.). (2010). *Recasting Transboundary Fisheries Management Arrangements in Light of Sustainability Principles: Canadian and International Perspectives*. Marinus Nijhoff / Brill.

Saha, N. K., Balakrishnan, M., & Batra, V. S. (2005). Improving industrial water use: case study for an Indian distillery. Resources, *Conservation and Recycling, 43*(2), 163-174.

Saha, R., & Rahman, M. (2013). *Green Brick Revolution in Bangladesh*. Paper presented at the International Conference on Climate Change Impact and Adaptation (I3CIA-2013), Center for Climate Change and Sustainability Research (3CSR), Department of Civil Engineering DUET Gazipur, Bangladesh.

SAI. (2012). *Sustainable sourcing of agricultural raw materials. A practitioner's guide*. Sustainable Agriculture Initiative Platform.

Sakai, M., & Barrett, J. (2016). Border carbon adjustments: Addressing emissions embodied in trade. *Energy Policy, 92*, 102-110.

Salacuse, J. (2015). *The Law of Investment Treaties, 2nd Edition*. Oxford: Oxford University Press.

Salat, S. (2011). *Cities and farms: on sustainable urbanism*. Paris, France: Hermann.

Salat, S., & Bourdic, L. (2011). *Factor 10: Multiplying by 10 resource productivity in the urban world Paper* presented at the SB11 Helsinki World Sustainable Building Conference, Helsinki.

Sammer, K., & Wüstenhagen, R. (2006). The influence of eco-labelling on consumer behaviour – results of a discrete choice analysis for washing machines. *Business Strategy and the Environment, 15*(3), 185-199.

Sandwith, T., Shine, C., Hamilton, L., & Sheppard, D. (2001). Transboundary Protected Areas for Peace and Co-operation. IUCN World Commission on Protected Areas, Best Practice Protected Area Guidelines Series No. 7.

Saphores, J.-D. M., & Nixon, H. (2014). How effective are current household recycling policies? Results from a national survey of US households. *Resources, Conservation and Recycling, 92*, 1-10.

Sarigiannis, D., Karakitsios, S., & Kermenidou, M. (2015). Health impact and monetary cost of exposure to particulate matter emitted from biomass burning in large cities. *Science of the total environment, 524-525*, 319-330.

Sauvant, K. p. (2015). The Negotiations of the United Nations Code of Conduct on Transnational Corporations: Experience and Lessons Learned. *The Journal of World Investment & Trade, 16*(1), 11-87.

Scealy, R., Newth, D., Gunasekera, D., & Finnigan, J. (2012). Effects of variation in grain sector response to climate change: An integrated assessment. *Economic Papers, 31*(3), 327-336.

Schandl, H., Hatfield-Dodds, S., Wiedmann, T., Geschke, A., Cai, Y., West, J., ... Owen, A. (2016). Decoupling global environmental pressure and economic growth: scenarios for energy use, materials use and carbon emissions. *Journal of Cleaner Production, 132*, 45-56.

Schandl, H., & West, J. (2010). Resource use and resource efficiency in the Asia–Pacific region. *Global Environmental Change, 20*(4), 636-647.

Scherr, S. (1999). *Soil Degradation: A Threat to Developing-Country Food Security by 2020? Food, Agriculture and the Environment Discussion Paper: 63*. Washington, D.C.: International Food Policy Research Institute.

Schilpzand, R., Liverman, D., Tecklin, D., Gordon, R., Pereira, L., Saxl, M., & Wiebe, K. (2010). Chapter 18 Governance Beyond the State: Non-state Actors and Food Systems. In J. Ingram, p. Ericksen, & D. Liverman (Eds.), *Food security and global environmental change*. London: Earthscan.

Schlager, E., & Ostrom, E. (1992). Property-rights regimes and natural resources: A conceptual analysis. *Land Economics, 68*(3), 249.

Schmidheiny, S. (1992). *Changing Course: a global business perspective on development and the environment*. Cambridge, Mass: MIT Press.

Schofield, C. (2011). The delimitation of maritime boundaries: an incomplete mosaic. In D. Wastl-Walter (Ed.), *The Ashgate Research Companion to Border Studies* (pp. 665–681).

Schofield, C. (Ed.) (2012). *Maritime Energy Resources in Asia: Legal Regimes and Cooperation. National Bureau of Asian Research Reports*.

Schrijver, N. (1997). *Sovereignty over natural resources: balancing rights and duties*. Cambridge: Cambridge University Press.

Schutyser, M. A. I., Pelgrom, p. J. M., van der Goot, A. J., & Boom, R. M. (2015). Dry fractionation for sustainable production of functional legume protein concentrates. *Trends in Food Science & Technology, 45*(2), 327-335.

SCPRAC. (n.d.). *SWITCH-Med SCP Policy Toolkit. Mainstreaming Sustainable Consumption and Production into Key Economic Sectors in the Mediterranean*. Produced by the Regional Activity Centre for Sustainable Consumption and Production of the Mediterranean Action Plan of the United Nations Environment Programme within the framework of the SWITCH-Med programme, financed by the European Union.

Seitz, M. A. (2007). A critical assessment of motives for product recovery: the case of engine manufacturing. *Journal of Cleaner Production, 15*, 1147-1157.

Senthilkumar, K., Mollier, A., Delmas, M., Pellerin, S., & Nesme, T. (2014). Phosphorus recovery and recycling from waste: An appraisal based on a French case study. *Resources, Conservation and Recycling, 87*, 97-108.

Seto, K. C., Dhakal, S., Bigio, A., Blanco, H., Delgado, G. C., Dewar, D., ... Ramaswami, A. (2014). Human Settlements, Infrastructure and Spatial Planning. In O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, p. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, & J. C. Minx (Eds.), *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom: Cambridge University Press.

Seufert, V., Ramankutty, N., & Foley, J. A. (2012). Comparing the yields of organic and conventional agriculture. *Nature, 485*(7397), 229-232.

Shaheen, S., & Cohen, A. (2013). *Innovative Mobility Carsharing*

Outlook, Summer 2013. Berkeley, CA: ransportation Sustainability Research Center, University of California at Berkeley.

Sharma, S. K., & Vairavamoorthy, K. (2009). Urban water demand management: prospects and challenges for the developing countries. *Water and Environment Journal, 23*(3), 210-218.

Sheldon, S., Hadian, S., & Zik, O. (2015). Beyond carbon: Quantifying environmental externalities as energy for hydroelectric and nuclear power. *Energy, 84*, 36-44.

Shell, R. D. (2012). *Future cities in a resource constrained world*. Available from: http://laverypennell.com/wp-content/uploads/2013/02/TED-Future-Cities-in-a-Resource-Constrained-World.pdf

Shen, B., Ghatikar, G., Lei, Z., Li, J., Wikler, G., & Martin, p. (2014). The role of regulatory reforms, market changes, and technology development to make demand response a viable resource in meeting energy challenges. *Applied energy, 130*, 814-823.

Shen, J., & Saijo, T. (2009). Does an energy efficiency label alter consumers' purchasing decisions? A latent class approach based on a stated choice experiment in Shanghai. *Journal of Environmental Management, 90*(11), 3561-3573.

Shi, G., Zhu, X., & Ban, H. (2016). Material properties and partial factors for resistance of high-strength steels in China. *Journal of Constructional Steel Research, 121*, 65-79.

Shiau, C.-S. N., Samaras, C., Hauffe, R., & Michalek, J. J. (2009). Impact of battery weight and charging patterns on the economic and environmental benefits of plug-in hybrid vehicles. *Energy Policy, 37*(7), 2653-2663.

Simon, B., Amor, M. B., & Földényi, R. (2016). Life cycle impact assessment of beverage packaging systems: focus on the collection of post-consumer bottles. *Journal of Cleaner Production, 112*, Part 1, 238-248.

Simon, D., McGregor, D., & Thompson, D. (2006). Contemporary perspectives on the peri-urban zones of cities in developing countries. In D. McGregor, D. Simon, & D. Thompson (Eds.), *The peri-urban interface: approaches to sustainable natural and human resource use* (pp. 3-17). London: Earthscan.

Simon, J. (2015). *Case study 4: the story of Contarina*. Available from: http://www.zerowasteeurope.eu/zw-library/case-studies/

Singh, B., Stromman, A., Hertwich, E., & Strømman, A. (2011). Comparative life cycle environmental assessment of CCS technologies. *International journal of greenhouse gas control, 5*(4), 911-921.

Smaller, C. (2014). *The IISD Guide to Negotiating Investment Contracts for Farmland and Water*. Winnipeg: International Institute for Sustainable Development (IISD).

Smith, M. (2011a). *Water Efficiency Opportunities – Best Practice Guide – Drink Processing - General*. Available from: http://www.environment.gov.au/water/publications/urban/weo-beverage-guide.html

Smith, M. (2011b). *Water Efficiency Opportunities – Best Practice Guide – Poultry Processing*. Available from: http://www.environment.gov.au/water/publications/urban/weo-poultry-guide.html

Smith, M. (2011c). *Water Efficiency Opportunities – Best Practice Guide – Steel Manufacturing*. Available from: http://www.environment.gov.au/water/publications/urban/weo-manufacturing-steel-guide.html

Smith, M. (2011d). *Water Efficiency Opportunities – Best Practice Guide – Wineries.* Available from: http://www.environment.gov.au/water/publications/urban/weo-wineries-guide.html

Smith, P., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E. A., ... Tubiello, F. (2014). Agriculture, Forestry and Other Land Use (AFOLU). In O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, p. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. v. Stechow, T. Zwickel, & J. C. Minx (Eds.), *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom: Cambridge University Press.

Smith, V. M., & Keoleian, G. A. (2004). The value of remanufactured engines. *Journal of Industrial Ecology, 8*(1-2), 193-221.

Sorrell, S., O'Malley, E., Schleich, J., & Scott, S. (2004). *The Economics of Energy Efficiency: Barriers to Cost-Effective Investment.* Cheltenham: Edward Elgar.

Sovacool, B. (2008). Valuing the greenhouse gas emissions from nuclear power: A critical survey. *Energy Policy, 36*(8), 2950-2963.

Spar, D., & La Mure, L. (2003). The Power of Activism: Assessing the Impact of NGOs on Global Business. *California management review, 45*(3), 78-101.

Speth, J. G., & Haas, p. (2009). *Global Environmental Governance: Foundations of Contemporary Environmental Studies*. Washington, D.C.: Island Press.

Staffell, I., & Rustomji, M. (2016). Maximising the value of electricity storage. *Journal of Energy Storage, 8*, 212-225.

Stanilov, K., & Scheer, B. C. (2004). *Suburban form: an international perspective*. New York: Routledge.

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., ... Sörlin, S. (2015). Planetary boundaries: Guiding human development on a changing planet. *Science, 347*(6223).

Stehfest, E., Bouwman, L., Vuuren, D. P., Elzen, M. G. J., Eickhout, B., & Kabat, p. (2009). *Climate benefits of changing diet* (Vol. 95).

Steinberger, J., Roberts, J. T., Peters, G., Baiocchi, G., & Timmons Roberts, J. (2012). Pathways of human development and carbon emissions embodied in trade. *Nature Climate Change, 2*(2), 81-85.

Steinhilper, R., & Weiland, F. (2015). Exploring New Horizons for Remanufacturing an Up-to-date Overview of Industries, Products and Technologies. *Procedia CIRP, 29*, 769-773.

Stern, N. (2008). The Economics of Climate Change. *The American Economic Review, 98*(2), 1-37.

Stern, N. (2013). The Structure of Economic Modeling of the Potential Impacts of Climate Change: Grafting Gross Underestimation of Risk onto Already Narrow Science Models. *Journal of Economic Literature, 51*(3), 838-859.

Stiglitz, J. E., Sen, A., & Fitoussi, J. p. (2009). *Report of the commission on the measurement of economic performance and social progress*.

Stolton, S., Shadie, P., & Dudley, N. (2013). *IUCN WCPA Best practice guidance on recognising protected areas and assigning management categories and governance types*. Gland, Switzerland: IUCN.

Suárez, S., Osorio, L., & Langford, M. (2009). *Voluntary Guidelines for Good Governance in Land and Natural Resource Tenure: Civil Society Perspectives, FAO Land Tenure Working Paper 8*.

Subulan, K., Taşan, A. S., & Baykasoğlu, A. (2015). Designing an environmentally conscious tire closed-loop supply chain network with multiple recovery options using interactive fuzzy goal programming. *Applied Mathematical Modelling, 39*(9), 2661-2702.

Sundin, E., & Bras, B. (2005). Making functional sales environmentally and economically beneficial through product remanufacturing. *Journal of Cleaner Production, 13*, 913-925.

Sundin, E., Elo, K., Lee, H., & Mien Lee, H. (2012). Design for automatic end-of-life processes. *Assembly Automation, 32*(4), 389-398.

Sutherland, J. W., Adler, D. P., Haapala, K. R., & Kumar, V. (2008). A comparison of manufacturing and remanufacturing energy intensities with application to diesel engine production. *CIRP Annals - Manufacturing Technology*, 57(1), 5-8.

Sutton, M. A., Bleeker, A., Howard, C. M., Bekunda, M., Grizzetti, B., de Vries, W., ... International Nitrogen Initiative. (2013). *Our nutrient world: the challenge to produce more food and energy with less pollution*. Edinburgh: NERC/Centre for Ecology & Hydrology.

Sutton, M. A., van Grinsven, H., Billen, G., Bleeker, A., Bouwman, A. F., Bull, K., ... Winiwarter, W. (2011). The European Nitrogen Assessment: Summary for policy makers In M. A. Sutton, C. M. Howard, J. W. Erisman, G. Billen, A. Bleeker, p. Grennfelt, H. J. M. van Grinsven, & B. Grizzetti (Eds.), *The European Nitrogen Assessment: Sources, Effects and Policy Perspectives* (pp. xxiv-xxxiv). Cambridge: Cambridge University Press.

Swamy, H. M. S., & Bhakuni, N. (2014). Towards integrated land use transport plan. *Journeys, May, 2014*.

Switch-Asia. (n.d.). *Satisfying Basic Needs Respecting the Earth's Limits*. Wuppertal: UN Environment/Wuppertal Institute Collaborating Centre on Sustainable Consumption and Production (CSCP).

Takiguchi, H., & Takemoto, K. (2008). Japanese 3R Policies Based on Material Flow Analysis. *Journal of Industrial Ecology, 12*(5-6), 792-798.

Taptich, M. N., Horvath, A., & Chester, M. V. (2016). Worldwide Greenhouse Gas Reduction Potentials in Transportation by 2050. *Journal of Industrial Ecology, 20*(2), 329-340.

Tasaki, T., Motoshita, M., Uchida, H., & Suzuki, Y. (2013). Assessing the Replacement of Electrical Home Appliances for the Environment. *Journal of Industrial Ecology, 17*(2), 290-298.

Tasaki, T., & Yamakawa, H. (2011). An estimation of the effectiveness of waste prevention by using point-of-sales (POS) data—The case of refills for shampoo and hair conditioner in Japan. *Resources, Conservation and Recycling, 57*, 61-66.

TCRP. (2008). *Effects of TOD on Housing, Parking, and Travel. TCRP Report 128.* Available from: http://onlinepubs.trb.org/onlinepubs/tcrp/tcrp_rpt_128.pdf

TCRP. (2015). *Quantifying transit's impact on GHG emissions and energy use - the land use component. TCRP Report 176*. Available from: http://onlinepubs.trb.org/onlinepubs/tcrp/tcrp_rpt_176.pdf

Tewari, p. K., Batra, V. S., & Balakrishnan, M. (2007). Water management initiatives in sugarcane molasses based distilleries in India. *Resources, Conservation and Recycling, 52*(2), 351-367.

Tewari, p. K., Batra, V. S., & Balakrishnan, M. (2009). Efficient water use in industries: Cases from the Indian agro-based pulp and paper mills. *Journal of Environmental Management, 90*(1), 265-273.

The Co-op. (2015). *Co-op Way Reporting 2015*. Available from: http://www.coop.co.uk/Corporate/PDFs/sustainability/Co-op_Way_2015-Sustainability_Report.pdf

The Louis Berger Group. (2004). *Emissions benefits of land use planning strategies. FHWA TOPR 29*. FHWA TOPR 29. Federal Highway Administration, USDOT.

Thornley, P., Gilbert, P., Shackley, S., & Hammond, J. (2015). Maximizing the greenhouse gas reductions from biomass: The role of life cycle assessment. *Biomass & bioenergy, 81*, 35-43.

Thorstad, E., Okland, F., Aarestrup, K., Heggberget, T., & Økland, F. (2008). Factors affecting the within-river spawning migration of Atlantic salmon, with emphasis on human impacts. *Reviews in Fish Biology and Fisheries, 18*(4), 345-371.

Tian, J., Liu, W., Lai, B., Li, X., & Chen, L. (2014). Study of the performance of eco-industrial park development in China. *Journal of Cleaner Production, 64*, 486-494.

Tienhaara, K. (2011). Regulatory chill and the threat of arbitration: A view from political science. In C. Brown & K. Miles (Eds.), *Evolution in Investment Treaty Law and Arbitration*. Cambridge: Cambridge University Press.

Tilman, D., & Clark, M. (2014). Global diets link environmental sustainability and human health. *Nature, 515*(7528), 518-522.

Tilton, J. E., & Lagos, G. (2007). Assessing the long-run availability of copper. *Resources Policy, 32*(1–2), 19-23.

Timperley, J. (2016). Flextricity unveils 'demand turn-up' system for harnessing wasted wind energy. *Business Green*.

Tompkins, E. (2008). *Development Pressures and Management Considerations in Small Caribbean Islands' Coastal Zones. CSERGE Working Paper ECM 03–08*.

Toulmin, C., & Quan, J. (Eds.). (2000). *Evolving Land Rights, Policy and Tenure in Africa*: IIED / DFID.

Truttman, N., & Rechberger, H. (2006). Contribution to resource conservation by re-use of electrical and electronic household appliances. *Resources Conservation and Recycling, 48*, 249-262.

Tsiliyannis, C. A. (2005). Parametric analysis of environmental performance of reused / recycled packaging. *Environmental Science and Technology, 39*, 9770-9777.

TUI. (2013). *Sustainable Holidays Report 2013.* TuiTravel Plc.

Tukker, A. (2005). Leapfrogging into the future: developing for sustainability. International *Journal of Innovation and Sustainable Development, 1*(1-2), 65-84.

Tukker, A., Emmert, S., Charter, M., Vezzoli, C., Sto, E., Munch Andersen, M., ... Lahlou, S. (2008). Fostering change to sustainable consumption and production: an evidence based view. *Journal of Cleaner Production, 16*(11), 1218-1225.

Tukker, A., & Jansen, B. (2006). Environmental Impacts of Products: A Detailed Review of Studies. *Journal of Industrial Ecology, 10*(3), 159-182.

Tuncer, B. (2013). *Engaging with consumers towards sustainable consumption. Strategies and experiences from the SWITCH-Asia programme. Scaling up study 2013*. SWITCH-Asia Network Facility.

Ueckerdt, F., Brecha, R., & Luderer, G. (2015). Analyzing major challenges of wind and solar variability in power systems. *Renewable Energy, 81*, 1-10.

UK-NCC. (2013). *The State of Natural Capital: Towards a framework for measurement and valuation*. London: UK Natural Capital Committee (UK-NCC).

UN-ESCAP. (2013). *The Status of the Water-Food-Energy Nexus in Asia and the Pacific. Discussion Paper. United Nations Economic and Social Commission for Asia and the Pacific.*

UN-Habitat. (2009). *Planning Sustainable Cities: Global Report on Human Settlements 2009. United Nations Human Settlements Programme*: Earthscan.

UN-Water. (2008). Transboundary Waters: Sharing Benefits, Sharing Responsibilities. Thematic Paper.

UN-Water. (2016). *Towards a worldwide assessment of freshwater quality. A UN-Water analytical brief.* Available from: http://www.unwater.org/fileadmin/user_upload/unwater_new/docs/UN_Water_Analytical_Brief_20161111_02_web_pages.pdf

UN. (2013). *A new global partnership: eradicate poverty and transform economies through sustainable development*. The report of the High-Level Panel of Eminent Persons on the post-2015 development agenda. New York: United Nations.

UN. (2014). *World Urbanization Prospects: The 2014 Revision, Highlights (ST/ESA/SER.A/352).* New York: United Nations, Department of Economic and Social Affairs, Population Division.

UN. (2015a). *The Millennium Development Goals Report 2015*. New York: United Nations.

UN. (2015b). *Transforming our world: the 2030 agenda for sustainable development*. New York: United Nations.

UN. (2015c). *World Population Prospects: The 2015 Revision, Key Findings and Advance Tables*. New York: United Nations.

UN, European Commission, OECD, & World Bank. (2014). System of Environmental-Economic Accounting 2012 Experimental Ecosystem Accounting.

UN, EU, FAO, IMF, OECD, & World Bank. (2014). System of Environmental–Economic Accounting 2012 Central Framework.

UNCLOS. (1982). *United Nations Convention of the Law of the Sea (UNCLOS), adopted 10 December 1982, in force 16 November 1994*, 1833 UNTS 397.

UNCTAD. (2009). *United Nations Conference on Trade and Development. World Investment Report 2009: Transnational Corporations, Agricultural Production, and Development*. UNCTAD/WIR/2009.

UNCTAD. (2011). *Water for Food-Innovative water management techniques for food security and poverty alleviation. Current Studies on Science, Technology and Innovation. Number 4.*

UNCTAD. (2014). *World Investment Report 2014: Investing in the SDGs: An Action Plan*. UNCTAD/WIR/2014.

UNCTAD. (2015). United Nations Conference on Trade and Development World Investment Report 2015: Reforming International Investment Governance. UNCTAD/WIR/2015.

UNDESA. (2012). A guidebook to the Green Economy. Issue 3: exploring green economy policies and international experience with national strategies. New York: UNDESA.

UNDESA. (2015). *Global Sustainable Development Report 2015 Edition*. Available from: https://sustainabledevelopment.un.org

UNDP. (2009). *Capacity Development: A UNDP Primer*. New York: UNDP.

UNDP. (2014). United Nations Development Programme Global Anti-Corruption Initiative (GAIN) 2014–2017.

UNDP Bangladesh. (2010). GREEN Brick (Improving Kiln Efficiency in

the Brick Making Industry). Available from: http://www.bd.undp.org/content/bangladesh/en/home/operations/projects/environment_and_energy/improving-kiln-efficiency-in-brick-making-industry-.html

UN Environment-MercoNet. (2011). *Resource Efficiency in Latin America: Economics and Outlook. Case Studies: MERCOSUR, Chile and Mexico. Executive Summary.*

UN Environment-SBCI. (2009). *Buildings and Climate Change. Summary for Decision-Makers*. Available from: http://www.unep.org/sbci/pdfs/sbci-bccsummary.pdf

UN Environment-SBCI. (2012). *Building Design and Construction: Forging Resource Efficiency and Sustainable Development*. Available from: http://www.unep.org/sbci/pdfs/UNEP_SBCI_PositionPaperJune2012.pdf

UN Environment. (1997). *World Atlas of Desertification, 2nd Edition. Middleton N. and Thomas D.S.G. (Eds.).* London: Edward Arnold.

UN Environment. (2009a). *Capacity Building for Sustainable Public Procurement*. Available from: http://www.unep.fr/scp/marrakech/pdf/SP2pager_eu.pdf

UN Environment. (2009b). *Towards sustainable production and use of resources: assessing biofuels. Stefan Bringezu, Helmut Schütz, Meghan O'Brien, Lea Kauppi, Robert W. Howarth and Jeff McNeely*. Paris, France: UN Environment.

UN Environment. (2010). *Assessing the environmental impacts of consumption and production: priority products and materials. A report of the Working Group on the Environmental Impacts of Products and Materials to the International Panel for Sustainable Resource Management. Hertwich, E., van der Voet, E., Suh, S., Tukker, A, Huijbregts M., Kazmierczyk, P., Lenzen, M., McNeely, J., Moriguchi, Y.* Paris, France: UN Environment.

UN Environment. (2011a). *Assessing the environmental impacts of consumption and production: priority products and materials. A report of the working group on the environmental impacts of products and materials to the International Panel for Sustainable Resource Management*. Hertwich, E., van der Voet, E., Suh, S., Tukker, A, Huijbregts M., Kazmierczyk, P., Lenzen, M., McNeely, J., Moriguchi, Y. Paris, France: UN Environment.

UN Environment. (2011b). *Decoupling natural resource use and environmental impacts from economic growth. A report of the Working Group on Decoupling to the International Resource Panel*. Nairobi: UN Environment.

UN Environment. (2011c). *Green Economy Report*. Nairobi: UN Environment.

UN Environment. (2011d). Recycling Rates of Metals – A Status Report, A Report of the Working Group on the Global Metal Flows to the International Resource Panel. Graedel, T.E.; Allwood, J.; Birat, J.-P.; Reck, B.K.; Sibley, S.F.; Sonnemann, G.; Buchert, M.; Hagelüken, C.

UN Environment. (2011e). *Taking Steps toward Marine and Coastal Ecosystem-Based Management - An Introductory Guide*.

UN Environment. (2012a). The Environmental Dimension of IFSD. UNEP Division of Environmental Law and Conventions Issues Brief # 2.

UN Environment. (2012b). *Global Environment Outlook 5: Environment for the future we want*. Available from: http://web.unep.org/geo/sites/unep.org.geo/files/documents/geo5_report_full_en_0.pdf

UN Environment. (2012c). *The Impacts of Sustainable Public Procurement. Eight Illustrative Case Studies*. Available from: http://www.unep.fr/scp/procurement/docsres/ProjectInfo/StudyonImpactsofSPP.pdf

UN Environment. (2012d). *Measuring water use in a green economy, A Report of the Working Group on Water Efficiency to the International Resource Panel. McGlade, J., Werner, B., Young, M., Matlock, M., Jefferies, D., Sonnemann, G., Aldaya, M., Pfister, S., Berger, M., Farell, C., Hyde, K., Wackernagel, M., Hoekstra, A., Mathews, R., Liu, J., Ercin, E., Weber, J.L., Alfieri, A., Martinez-Lagunes, R., Edens, B., Schulte, P., von Wirén-Lehr, S., Gee, D.*

UN Environment. (2013a). City-Level Decoupling: Urban resource flows and the governance of infrastructure transitions. A Report of the Working Group on Cities of the International Resource Panel. Swilling M., Robinson B., Marvin S. and Hodson M.

UN Environment. (2013b). *Environmental risks and challenges of anthropogenic metals flows and cycles. A report of the Working Group on Global Metal Flows to the International Resource Panel. van der Voet, E., Salminen, R., Eckelman, M., Mudd, G., Norgate, T., Hischier, R.*

UN Environment. (2013c). *Metal recycling: opportunities, limits, infrastructure. A report of the Working Group on the Global Metal Flows to the International Resource Panel. Reuter, M.A., Hudson, C., van Schaik, A., Heiskanen, K., Meskers, C., Hegeluken, C.*

UN Environment. (2014a). *Assessing Global Land Use: Balancing Consumption with Sustainable Supply. A Report of the Working Group on Land and Soils of the International Resource Panel.*

UN Environment. (2014b). *Decoupling 2: technologies, opportunities and policy options. A report of the Working Group on Decoupling to the International Resources Panel.*

UN Environment. (2014c). *Guidance document on programme development and implementation for the Ten Year Framework of Programmes on Sustainable Consumption and Production (10YFP): Criteria, structure and steps to develop and operationalize them.* DRAFT 6 Available from: http://www.unep.org/10yfp/Portals/50150/Guidance_Doc_10YFP_Programmepercent20development_1_V1_March14.pdf

UN Environment. (2014d). *Sand, rarer than one thinks. UNEP Global Environmental Alert Service.* Nairobi: UN Environment.

UN Environment. (2014e). *Sustainable Consumption and Production (SCP) Targets and Indicators and the SDGs. UNEP Post-2015 Discussion Paper. June 2014.*

UN Environment. (2015a). *The Emissions Gap Report, a UNEP Synthesis Report.* Nairobi: UN Environment.

UN Environment. (2015b). *Green Energy Choices: The benefits, risks, and trade-offs of low-carbon technologies for electricity production. E.G. Hertwich, T. Gibon, S. Suh, J. Aloisi de Larderel, A. Arvesen, p. Bayer, J. Bergesen, E. Bouman, G. Heath, C. Peña, p. Purohit, A. Ramirez*. Paris, France: UN Environment.

UN Environment. (2015c). *The International Resource Panel: 10 key messages on Climate Change*. Paris, France: UN Environment.

UN Environment. (2015d). *International Trade in Resources: A Biophysical Assessment, Report of the International Resource Panel*. Paris, France: UN Environment.

UN Environment. (2015e). Options for decoupling economic growth from water use and water pollution. Report of the International Resource Panel Working Group on Sustainable Water Management. Paris, France: UN Environment.

UN Environment. (2015f). *Policy Coherence of the Sustainable Development Goals: a Natural Resource Perspective*. Paris, France: UN Environment.

UN Environment. (2016a). *Global material flows and resource productivity. An assessment study of the International Resource Panel*. Paris, France: UN Environment.

UN Environment. (2016b). *Green Energy Choices: The benefits, risks and trade-offs of low-carbon technologies for electricity production.Report of the International Resource Panel. E. G. Hertwich, J. Aloisi de Larderel, A. Arvesen, p. Bayer, J. Bergesen, E. Bouman, T. Gibon, G. Heath, C. Peña, p. Purohit, A. Ramirez, S. Suh, (eds.).* Paris, France: UN Environment.

UN Environment. (2016c). Resource efficient and cleaner production. Available from: http://www.unep.org/recp/

UN Environment. (2016d). *Summary for Policy Makers of the IRP report for the G7. Resource efficiency: potential and economic implications*. International Resource Panel. Paris, France: UN Environment.

UN Environment. (2016e). *Unlocking the Sustainable Potential of Land Resources: Evaluation Systems, Strategies and Tools. A Report of the Working Group on Land and Soils of the International Resource Panel. Herrick, J.E., O. Arnalds, B. Bestelmeyer, S. Bringezu, G. Han, M.V. Johnson, D. Kimiti, Yihe Lu, L. Montanarella, W. Pengue, G. Toth, J. Tukahirwa, M. Velayutham, G. Zhang*. Paris, France: UN Environment.

UN Environment, & CSIRO. (2011). *Resource efficiency: economics and outlook for Asia and the Pacific.* Available from: http://www.unep.org/dewa/Portals/67/pdf/Resource_Efficiency_EOAP_web.pdf

UN Environment, & UNWTO. (2012). *Tourism in the Green Economy – Background Report, UNWTO, Madrid*. Available from: http://web.unep.org/greeneconomy/sites/unep.org.greeneconomy/files/field/image/tourism_in_the_green_economy_unwto_unep.pdf

UNESC. (2015a). *Terms of reference for the Inter-agency Expert Group on Sustainable Development Goal Indicators*. Available from: http://unstats.un.org/

UNESC. (2015b). *UN Economic and Social Council (ESC) Report to the Inter-Agency and Expert Group on Sustainable Development Goal Indicators. 17 December 2015, E/CN.3/2016/2*.

UNFCCC. (2015). *The Paris Agreement*. Available from: http://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf

UNFT. (2012). *United Nations Interagency Framework Team for Preventive Action (UNFT) Toolkit and Guidance for Preventing and Managing Land and Natural Resources Conflict: Land and Conflict, 2012*.

UNGA. (1962). *Permanent Sovereignty over Natural Resources, G.A. res. 1803 (XVII), 17 U.N. GAOR Supp. (No.17) at 15, U.N. Doc. A/5217 (1962).*

UNIDO. (2013). *Green growth: from labour to resource productivity – best practice examples, initiatives and policy options.* Available from: https://www.unido.org/fileadmin/user_media_upgrade/Media_center/2013/GREENBOOK.pdf

UNIDO, & UN Environment. (2015). *National Cleaner Production Centres - 20 years of achievement. Towards decoupling resource use and environmental impact from manufacturing growth*. Available from: https://www.unido.org/fileadmin/user_media_upgrade/What_we_do/Topics/Resource-efficient__low-carbon_production/NCPC_20_years.pdf

UNSD. (2015). *National accounts main aggregates database*. New York: United Nations Statistics Division.

UNWTO. (2010). *Tourism and sustainability*. Madrid: UNWTO.

UNWTO. (2011). *Tourism Towards 2030: Global Overview*. Available from: http://ictur.sectur.gob.mx/descargas/Publicaciones/Boletin/cedoc2012/cedoc2011/unwto2030.pdf

USDA. (2011). *National Agronomy Manual. 190-V-NAM*. Available from: Washington, DC.: http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1043208.pdf

USITC. (2012). *Remanufactured goods: an overview of the US and global industries, markets and trade*. Washington, D.C.: USITC.

Van Berkel, R., Fujita, T., Hashimoto, S., & Geng, Y. (2009). Industrial and urban symbiosis in Japan: Analysis of the Eco-Town program 1997–2006. *Journal of Environmental Management, 90*(3), 1544-1556.

van der Kooij, S., Zwarteveen, M., Boesveld, H., & Kuper, M. (2013). The efficiency of drip irrigation unpacked. *Agricultural Water Management, 123*, 103-110.

van der Zwaan, B. (2013). The role of nuclear power in mitigating emissions from electricity generation. *Energy Strategy Reviews, 1*, 296-301.

Van Doorn, J., & Verhoef, p. C. (2015). Drivers of and Barriers to Organic Purchase Behavior. *Journal of Retailing, 91*(3), 436-450.

Van Ewijk, S., & Stegemann, J. A. (2014). Limitations of the waste hierarchy for achieving absolute reductions in material throughput. *Journal of Cleaner Production*.

van Grinsven, H. J. M., ten Berge, H. F. M., Dalgaard, T., Fraters, B., Durand, P., Hart, A., ... Willems, W. J. (2012). Management, regulation and environmental impacts of nitrogen fertilization in northwestern Europe under the Nitrates Directive; a benchmark study. *Biogeosciences, 9*(12), 5143-5160.

Van Harten, G. (2007). *Investment Treaty Arbitration and Public Law*. Oxford: Oxford University Press.

Van Vliet, A. (2013). *Case study 1: The story of Capannori*. Available from: http://www.zerowasteeurope.eu/zw-library/case-studies/

Vanclay, F., Esteves, A. M., Aucamp, I., & Francks, D. M. (2015). *Social Impact Assessment: Guidance for assessing and managing the social impacts of projects*. International Association for Impact Assessment.

Vandenhove, H., Sweeck, L., Vives I Batlle, J., Wannijn, J., Van Hees, M., Camps, J., ... Miliche, C. (2013). Predicting the environmental risks of radioactive discharges from Belgian nuclear power plants. *Journal of environmental radioactivity, 126*, 61-76.

Verma, A., Jaiswal, Y. K., & Wani, K. (2012). Energy Consumption Behaviour of an Urban Residential Sector in the Northern Province of Madhya Pradesh (India). *Indoor + built environment, 21*(5), 703-709.

Vermeulen, S. J., Campbell, B. M., & Ingram, J. S. I. (2012). Climate Change and Food Systems. *Annual Review of Environment and Resources, 37*(1), 195-222.

Viet, P., Larsen, G., & Easton, C. (2013). *Overlapping Property Rights: When Rights to Natural Resources Conflict with Rights to Land*. World Resources Institute / USAID.

Villanuevaa, A., & Wenzel, H. (2007). Paper waste – Recycling, incineration or landfilling? A review of existing life cycle assessments. *Waste Management, 27*(8), S29–S46.

Von Witzke, H., Noleppa, S., & Schwarz, G. (2008). *Global agricultural market trends and their impacts on European agriculture. Humboldt University Working Paper 84*.

Warner, R. (2009). Protecting the Oceans Beyond National Jurisdiction: *Strengthening the International Legal Framework*: Brill | Nijhoff.

Warren, p. (2014). A review of demand-side management policy in the UK. *Renewable and Sustainable Energy Reviews, 29*, 941-951.

Waughray, D. (Ed.) (2011). *Water Security: the water-food-energy-climate nexus*. Washington: Island Press.

WBCSD. (2000). *Measuring Eco-Efficiency: A guide to reporting company performance*. Geneva: WBCSD.

WCRF, & AICR. (2007). *Food, nutrition, physical activity and the prevention of cancer: a global perspective. 2nd Expert Report*. Washington, D.C.: World Cancer Research Fund / American Institute for Cancer Research.

Weaver, J. L., & Asmus, D. F. (2006). Unitizing Oil and Gas Fields Around the World: A comparative Analysis of National Laws and Private Contracts. *Houston Journal of International Law, 28*(3), 3-198.

Wei, S., Cheng, D., Sundin, E., & Tang, O. (2015). Motives and barriers of the remanufacturing industry in China. *Journal of Cleaner Production, 94*, 340-351.

Weibust, I., & Meadowcroft, J. (Eds.). (2014). *Multilevel Environmental Governance: Managing Water and Climate Change in Europe and North America*. Cheltenham: Edward Elgar.

Weiss, T. G., & Thakur, R. (2010). *Global Governance and the UN: An Unfinished Journey*. Indiana: Indiana University Press.

Weissbrodt, D., & Kruger, M. (2003). Norms on the Responsibilities of Transnational Corporations and Other Business Enterprises with Regard to Human Rights. *The American Journal of International Law, 97*(4), 901-922.

Weisser, D. (2007). A guide to life-cycle greenhouse gas (GHG) emissions from electric supply technologies. *Energy, 32*(9), 1543-1559.

Weizsäcker, E. V., Hargroves, K. M., Smith, H., Desha, C., & Stasinopoulos, p. (2009). *Factor 5: Transforming the Global Economy through 80% Increase in Resource Productivity*. London: Earthscan.

West, J., & Schandl, H. (2013). Material use and material efficiency in Latin America and the Caribbean. *Ecological Economics, 94*, 19-27.

West, J., Schandl, H., Heyenga, S., & Chen, S. (2013). *Resource Efficiency: Economics and Outlook for China*. Bangkok, Thailand: UN Environment.

West, J., Schandl, H., Krausmann, F., Kovanda, J., & Hak, T. (2014). Patterns of change in material use and material efficiency in the successor states of the former Soviet Union. *Ecological Economics, 105*, 211-219.

Westhoek, H., Lesschen, J. P., Leip, A., Rood, T., Wagner, S., De Marco, A., ... Sutton, M. A. (2015). *Nitrogen on the Table: The influence of food choices on nitrogen emissions and the European environment. (European Nitrogen Assessment Special Report on Nitrogen and Food.)*. Edinburgh: Centre for Ecology & Hydrology.

Westhoek, H., Lesschen, J. P., Rood, T., Wagner, S., De Marco, A., Murphy-Bokern, D., ... Oenema, O. (2014). Food choices, health and environment: Effects of cutting Europe's meat and dairy intake. *Global Environmental Change, 26*, 196-205.

Westhoek, H., Rood, T., van den Berg, M., Janse, J., Nijdam, D., Reudink, M., & Stehfest, E. (2011). *The protein puzzle. The consumption and production of meat, dairy and fish in the European Union*. The Hague: PBL Netherlands Environmental Assessment Agency.

WHO. (2007) Protein and Amino Acid Requirements in Human Nutrition. In FAO/UNU (Ed.), *WHO technical report series 935*. Geneva: World Health Organization.

Wiedmann, T. O., Schandl, H., Lenzen, M., Moran, D., Suh, S., West, J., & Kanemoto, K. (2015). The material footprint of nations. *Proceedings of the National Academy of Sciences, 112*(20), 6271-6276.

Wijkman, A., & Skånberg, K. (2015). *The Circular Economy and Benefits for Society*. Available from: https://www.clubofrome.org/wp-content/uploads/2016/03/The-Circular-Economy-and-Benefits-for-Society.pdf

Williams, R., Rademaekers, K., Smith, M., Zaki, S., & van Breugel, C. (2011). *Mid-term Evaluation of the Sustainable Consumption and Production and Sustainable Industrial Policy Action Plan*. Final report. Completed under the Framework Contract ENV.G.1/FRA/2006 on behalf of European Commission – DG Environment.

Wilson, W. T. (2013). *Hitting the sweet spot. The growth of the middle class in emerging markets*. Ernst & Young.

Wimmer, R. (2014). *Zero Carbon Resorts Project in the Philippines*. Paper presented at the International Conference on Hospitality and Tourism 2014, Colombo, Sri Lanka.

Wollebaek, J., Heggenes, J., Roed, K., Wollebæk, J., & Røed, K. (2011). Population connectivity: dam migration mitigations and contemporary site fidelity in arctic char. *BMC Evolutionary Biology, 11*(1), 207-207.

Woolridge, A. C., Ward, G. D., Phillips, p. S., Collins, M., & Gandy, S. (2006). Life cycle assessment for reuse/recycling of donated waste textiles compared to use of virgin material: An UK energy saving perspective. *Resources, Conservation and Recycling, 46*(1), 94-103.

World Economic Forum. (2013). *Engaging tomorrow's consumer. A report by the World Economic Forum's Sustainable Consumption Initiative, prepared in collaboration with Accenture*.

WRAP. (2015a). Argos launches new gadget trade-in service at stores nationwide. Available from: http://www.wrap.org.uk/content/argos-launches-new-gadget-trade-service-stores-nationwide

WRAP. (2015b). Argos: Gadget Trade-in. Available from: http://www.wrap.org.uk/content/argos-gadget-trade

WRAP. (2016a). The Courtauld Commitment. Available from: http://www.wrap.org.uk/node/14507

WRAP. (2016b). Innovative business models. Available from: http://www.wrap.org.uk/content/innovative-business-models-1

WSA. (2015). *Sustainable Steel—policy and indicators 2015*. Brussels, Belgium: World Steel Association.

WTO. (1994). *Agreement Establishing the World Trade Organization, 15 April 1994, Preamble*. Geneva: WTO.

WTO. (2014). *World Trade Report 2014. Trade and development: recent trends and the role of the WTO. Geneva*: WTO.

WTO. (2015). World Trade Organisation. Environment: Issues, Sustainable Development. Available from: https://www.wto.org/english/tratop_e/envir_e/sust_dev_e.htm

WTTC. (2014). *Travel & Tourism: Economic Impact 2014*. London: World Travel and Tourism Council.

WWAP. (2015). *The United Nations World Water Development Report 2015: water for a sustainable world*. Paris, France: WWAP

WWF. (2001). *Guidelines for community-based ecotourism development*. Available from: http://www.widecast.org/Resources/Docs/WWF_2001_Community_Based_Ecotourism_Develop.pdf

WWF. (2012). Curitiba waste as resource. Available from: http://wwf.panda.org/?204414/Curitiba-waste-as-resource

WWF, & Friends of Europe. (2015). *The future of food - building the foundations for change*. Geneva: World Wildlife Fund.

Xu, J. (2002). River sedimentation and channel adjustment of the lower Yellow River as influenced by low discharges and seasonal channel dry-ups. *Geomorphology, 43*(1-2), 151-164.

Yandle, T. (2007). Understanding the consequences of property rights mismatches: a case study of New Zealand's marine resources. *Ecology and Society, 12*(2).

Yang, Q., Yu, S., & Jiang, D. (2014). A modular method of developing an eco-product family considering the reusability and recyclability of customer products. *Journal of Cleaner Production, 64*, 254-265.

Yoshikawa, N., Fujiwara, N., Nagata, J., & Amano, K. (2016). Greenhouse gases reduction potential through consumer's behavioral changes in terms of food-related product selection. *Applied energy, 162*, 1564-1570.

Young, H., & Goldman, L. (Eds.). (2015). *Livelihoods, Natural Resources, and Post-Conflict Peacebuilding*. London: Routledge.

Young, O. R. (Ed.) (1997). *Global Governance: Drawing Insights from the Environmental Experience*. MIT Press.

Young, O. R., King, L. A., & Schroeder, H. (2008). *Institutions and Environmental Change: Principal Findings, Applications and Research Frontiers*. MIT Press.

Yu, C., Dijkema, G. p. J., de Jong, M., & Shi, H. (2015). From an eco-industrial park towards an eco-city: a case study in Suzhou, China. *Journal of Cleaner Production, 102*, 264-274.

www.unep.org

UN Environment
P.O. Box 30552 - 00100 Nairobi, Kenya
Tel.: +25420 762 1234
Fax: +254 20 762 3927
e-mail: publications@unep.org
www.unep.org

UN environment
United Nations Environment Programme

Despite enormous progress in the past decades towards improving human prosperity and well-being, this has come at the lasting cost of degradation of the natural environment and depletion of natural resources. Meeting the needs of a growing and increasingly affluent population, will require natural resource use to increase from 85 to 186 billion tonnes by 2050. This can cause irreversible environmental damage and endanger the capacity of Earth to continue to provide resources which are essential for human survival and development.

Analysis in the report shows that policies and initiatives to improve resource efficiency and tackle climate change can reduce global resource extraction by up to 28 per cent while also boosting the value of world economic activity by 1 per cent in 2050, against the baseline. Such policy actions can also cut global greenhouse gas emissions by around 60 per cent in 2050 relative to 2015 levels.

This report has been produced by the International Resource Panel hosted by UN Environment in response to a request by leaders of the G7 nations in the context of efforts to promote resource efficiency as a core element of sustainable development. The report conducts a rigorous survey to assess and articulate the prospects and solutions for resource efficiency. It considers how more efficient use of resources can contribute to economic growth, employment and development, at the same time as reducing the world's use of materials, energy, biomass and water, and the resulting environmental impacts.

The report documents many examples of best practices for increasing the resource efficiency of different sectors from countries around the world. The challenge for policy-makers is to learn from and scale up these good practices, and to conceive and implement a set of transformative policies that will enable countries to reap the associated social, environmental and economic benefits. Ambitious action to use resources in a more efficient and sustainable manner can help place the world on the right track to meet its commitments under the 2030 Agenda on Sustainable Development and the Paris Climate Change Agreement, and thereby to realise a more equitable and sustainable future.

For more information contact:
International Resource Panel Secretariat
UN Environment
Economy Division
Email: resourcepanel@unep.org
Web: www.unep.org/resourcepanel