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BRINGING VARIABLE RENEWABLE ENERGY UP TO SCALE

Options for Grid Integration Using Natural Gas and Energy Storage

ESMAP MISSION

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Energy Sector Management Assistance Program | The World Bank

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ACRONYMS AND ABBREVIATIONS

AGC	Automatic generation control
CAES	Compressed air energy storage
CAISO	California Independent System Operator
CCGT	Combined cycle gas turbine
CES	Community energy storage
CO_2	Carbon dioxide
CPV	Concentrated photovoltaics
CSP	Concentrating solar power
CT	Combustion turbine
DES	Distributed energy storage
DR	Demand response
DSM	Demand-side management
GHG	Greenhouse gas
GWEC	Global Wind Energy Council
HTF	Heat transfer fluid
LAES	Liquid air energy storage
LCOE	Levelized cost of electricity
LNG	Liquefied natural gas
MAE	Mean absolute error
MT	Micro- or mini-turbine
NaS	Sodium sulfur (battery)
NERC	North American Electric Reliability Corporation
NG	Natural gas
O&M	Operations and maintenance
OCGT	Open cycle gas turbine
PJM	PJM Interconnection, LLC (a regional transmission organization, US)
PV	Photovoltaic
R&D	Research and development
RD&D	Research, development and deployment
RE	Renewable energy
SMES	Superconducting magnetic energy storage
T&D	Transmission and distribution
TES	Thermal energy storage
VRE	Variable renewable energy

All currency in United States dollars (USD or US$), unless otherwise indicated.

ACKNOWLEDGMENTS

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The final synthesis was written by Silvia Martinez (Senior Energy Specialist, ESMAP) under the guidance of Wendy Hughes (Lead Specialist, ESMAP) and Rohit Khanna (Program Manager, ESMAP). Recent developments and findings described in published reports, as well as additional information obtained in conferences, knowledge sharing events, and expert interviews were used to provide an updated overview on the topic.

The work on Renewable Energy Integration was initiated by Natalya Kulichenko (Senior Energy Specialist, World Bank) and supported by Michael Levitsky (Senior Energy Specialist, World Bank) and Silvia Martinez Romero. In a second stage, Silvia Martinez led the project to completion with the assistance of Rafael Ben (Renewable Energy Specialist, consultant). Substantial guidance was received by Marcelino Madrigal (Senior Energy Specialist, World Bank), Pierre Audinet (Clean Energy Team Leader, ESMAP), and Rohit Khanna (Program Manager, ESMAP). Comments from Marcelino Madrigal, Rhonda Lenai (Energy Specialist, World Bank), Karen Bazex (Energy Specialist, World Bank), Robert Lesnick (Senior Energy Specialist, World Bank), Istvan Dobozi (consultant), Almudena Mateos (Energy Specialist, ESMAP), and Guillermo Hernandez (Energy Specialist, World Bank) were greatly appreciated. Special thanks to the peer reviewers of the internal consolidated report: Kwawu Mensan Gaba (Lead Energy Specialist, World Bank), Sergio Augusto Gonzalez (Senior Energy Specialist, World Bank), and Alan F. Townsend (Senior Energy Specialist, World Bank).

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EXECUTIVE SUMMARY

By the end of 2013, 144 countries—both developed and developing—had established plans for the expansion of power generation from renewable energy (REN 21). In setting these goals, countries are driven by a number of strategic considerations, including energy security, reducing pollution and greenhouse gas emissions, the need to expand and improve energy services for growing populations, and industrialization and job creation.

Among renewable energy sources, solar and wind resources stand out as having high inherent resource variability and limited predictability. For this reason, solar and wind generation technologies are often referred to as Variable Renewable Energy (VRE). Ten years ago, VRE technologies appealed primarily to those willing to pay a premium to move away from fossil fuels for environmental reasons. Today, due to equipment cost reductions, VRE is becoming competitive, putting the possibility of achieving high shares of VRE within reach of a growing number of countries.

To achieve a reliable, stable power supply, power system operators must continuously balance supply and demand. Power systems are designed to handle a certain amount of variability and uncertainty to accommodate fluctuations in demand and unexpected equipment outages. At modest levels of VRE contribution (i.e., below 5 to 10 percent, depending on the characteristics of the power system), the variability and uncertainty introduced by VRE are about the same order of magnitude as those due to normal fluctuations in demand. At this level, VRE integration can usually be managed with adjustments in operational strategies without significant investment.

But as the share of VRE increases, the higher levels of generation variability and uncertainty exceed the range that can be accommodated through operational adjustments. Additional measures are needed to avoid negative impacts on grid performance. With the promise of deriving a high share of power generation from VRE comes the challenge of integration: managing increasing levels of variability and uncertainty while maintaining performance and keeping costs down.

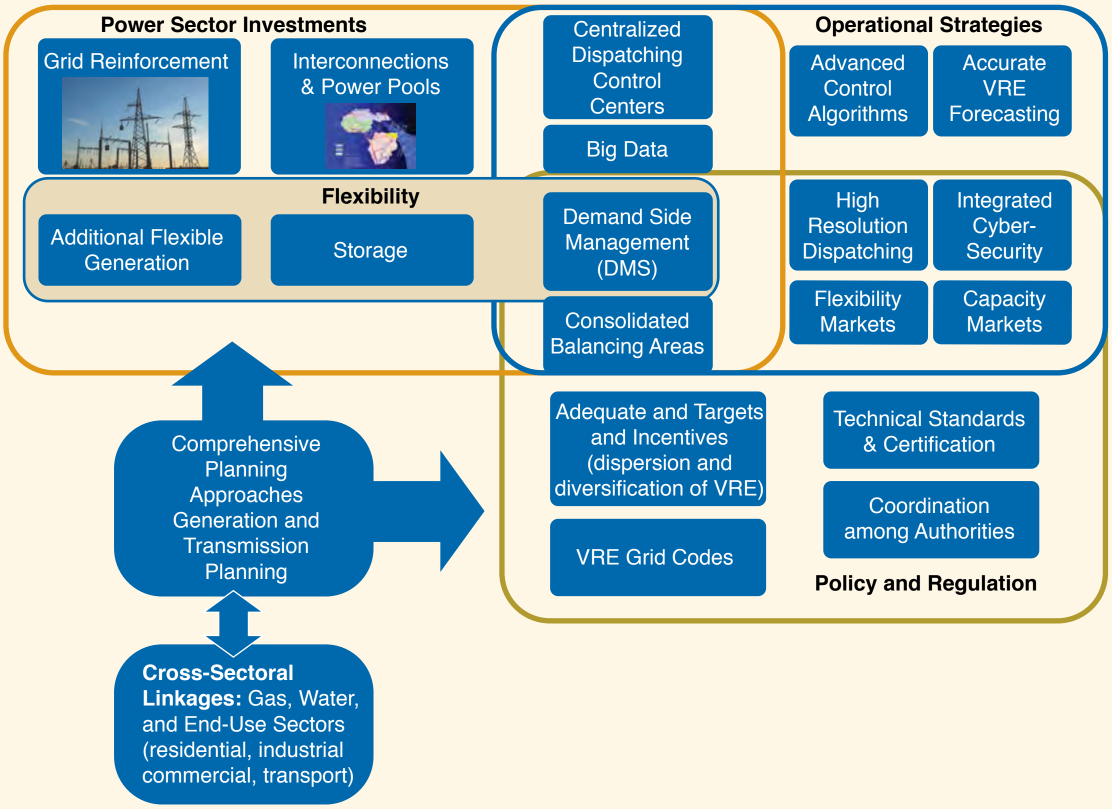
This report looks at the nature of VRE and the resulting challenges associated with the integration of VRE technologies into a power system. It provides an overview of the measures available to limit and manage these challenges. This report highlights the importance of increased flexibility when integrating high levels of VRE, and focuses on two sets of options to provide such flexibility: natural gas-fired power generation technologies and energy storage. Finally, this report provides some insight into the implications of VRE expansion for planning and regulation, and finishes with some recommendations for planners and policy makers.

A recent study (IEA, 2014) shows that if appropriate measures are taken to address VRE integration issues, it is possible to integrate levels of VRE even above 30 percent at modest incremental cost. To achieve this, power system planning, regulatory, and policy measures will need to be undertaken with the objective of minimizing total system costs, rather than minimizing VRE generation costs alone. A comprehensive planning process would make use of advanced modeling to evaluate the impact of VRE on the power system, optimize siting and timing of new VRE, and evaluate the progressive introduction of a suite of measures available to facilitate successful VRE integration into the system.

It is advisable to consider the full range of options and select a package best suited to the existing system and objectives. Figure 1 sets out a number of options that can be utilized to manage VRE integration, organized around operational strategies, policy and regulation, and investments.

FIGURE 1

Main Measures to Reduce and Manage Generation Variability and Uncertainty at High Levels of VRE



Source | Adapted by authors from WB information and other sources.

When analyses show that additional investments in flexibility are required to ensure the reliability of the system at high shares of VRE, the specific performance requirements are key for the identification of the most suitable technologies, and should be included in the simulations used for decision making. Depending on the existing demand and energy mix, system flexibility can be increased through options that act on the supply side (i.e., generation technologies that can be started-up, shut-down, and controlled to adjust power output quickly and frequently without having major impact on the equipment's life), on the demand side (i.e., by making adjustments to the demand, for example through demand response management supported by smart-grid technologies), or on both supply and demand using storage technologies. Flexible generators, such as reservoir hydropower plants or modern gas turbines and combined cycles, and demand response can quickly adjust power supply and demand, respectively, to compensate for changes in VRE output. Storage can shift generation or load as necessary to fill the gap between VRE generation and demand.

NATURAL GAS AS AN OPTION FOR SUPPLY FLEXIBILITY

Natural gas (NG) generation can contribute to addressing some of the issues associated with VRE integration. Whereas coal[1] or nuclear steam cycle generators can take more than 12 hours to reach full load, some gas combustion technologies have start-up times measured in minutes. Start-up and ramp-up rates (i.e., how quickly the generation output can increase or decrease) for NG generation systems vary with technology and installed capacity but are generally faster than other thermal technologies. Part-load efficiency of NG-fired technologies is also higher than coal-fired power plants. In simple cycle, start-up times (from hot start) for gas turbines are about 10 to 15 minutes. Gas reciprocating engines can start and ramp up to full load more quickly. Combined cycle gas turbine (CCGT) power plants are the most common NG option for base-load and non-peak operations due to their capacity range and high efficiency at full load. Current CCGTs require approximately 100 to 150 minutes for hot start-up. New, "fast-acting" CCGTs can achieve full load output in less than 40 minutes (NOVI Energy 2012).

NG generators do have limitations in start-up times, ramp rates, and turn-down ratios (i.e., the minimum power output at which the generator can operate), so there is a limit to the amount and type of flexibility they can provide. In addition, part load operation increases emissions and maintenance costs per unit generated, and reduces the operating life of the equipment.

ENERGY STORAGE AS AN OPTION FOR FLEXIBILITY

Energy storage offers another set of options to provide flexibility in the power system. Technologies are available in a diversity of forms, and can be incorporated at various locations within the electricity system from bulk supply through to individual consumer level. Pumped hydro, compressed air energy storage, multiple battery technologies, and thermal storage are generally the preferred technologies for energy time shift and VRE balancing applications. Flywheels, high-power lithium-ion batteries, and super capacitors are typically the preferred technologies for rapid-response operations such as VRE load following and regulation reserves (DNV KEMA 2012).

Limitations on the use of advanced storage technologies include a generally higher cost than other alternatives and additional risk associated with limited operational experience and the resulting uncertainty about long-term performance and maintenance costs. The tendency for grid planners and operators is to first use other approaches for managing variability, or even to curtail VRE generation before including storage in their power system expansion plans. However, projected cost reductions in some advanced storage options, together with a growing track record of commercial operation, will likely make storage technologies candidates for consideration in longer term systems planning.

PLANNING AND POLICY CONSIDERATIONS

Financial viability of existing gas-fired power plants. In some countries with low demand growth, the shift to high shares of VRE has led to a considerable reduction in the utilization of conventional power capacity. When VRE plants are generating electricity, conventional plants (mostly gas-fired because of their flexibility) are forced to reduce output and move into a load-following mode. In some countries, the loss of revenues for gas-fired power plants has led to write-downs and, ultimately, to the decommissioning of some plants, as well as lack of appetite for new investment. This negative impact on existing gas-fired generation has potential implications for longer term adequacy and stability of the power grid as a consequence of the reduced investment in dispatchable, flexible plants. Several solutions have been proposed that would help remedy the current situation, and could be applied by authorities in countries at the beginning of a planned VRE scale up. The underlying concept is that certain services—such as firm capacity and flexibility—are essential in a system with high VRE penetration, and the value of these services should be recognized and compensated.

Implications for variability of NG demand. Another consideration is that variability in NG generation associated with an increasing share of VRE can have implications for NG demand. The close link between a scale up of VRE and the use of gas-fired power generation to provide power system flexibility may imply the need for some additional flexibility in gas supply. Policy-makers, planners, and system operators in the electricity and gas sectors need to consider the impact on the NG sector of high levels of VRE, and coordinate closely on planning, infrastructure investments, and operating rules, to achieve security of gas and electricity supplies.

Long-term planning should account for short-term imbalances. A comprehensive approach to planning can help to minimize VRE integration costs for the power system. The growing share of VRE must be taken into account in system planning to make sure that development plans and specifications for both VRE and conventional generation are aimed at achieving the least cost for the overall power system. For VRE, measures could include adequate targets and timeframes, geographical and technological diversification, and interconnection and inter-operability requirements. For conventional generation, they could include increasing the amount of flexible generation in the overall systems and adapting existing power plants and efficiency requirements. The performance of a power system is modeled at timescales, ranging from years to fractions of a second, and across spatial regions, from a local area to the whole system. System planning generally focuses over longer timeframes. However, some of the potential issues associated with VRE variability and limited predictability occur at timescales that are typically assessed in short-term simulations (e.g., verification of the sufficiency of load-following and regulation reserves, and dynamic stability analysis). Some potential solutions (such as adding additional flexible generation capacity) are easily assessed in long-term planning models, and others (such as implementing demand response measures) are more readily assessed in short-term models. Finding the optimal VRE integration approach may require an iterative modeling process between simulations of the impacts at the different timescales at which variability occurs and the least-cost long-term planning models, in order to achieve the specified level of reliability at the least overall system cost.

CONCLUSIONS AND RECOMMENDATIONS

To best manage the challenge of integrating higher levels of VRE into electricity grids, policy, planning and regulatory interventions should be designed to minimize overall system costs subject to meeting performance targets, rather than minimizing the costs of VRE generation alone.

A comprehensive approach to system planning that considers the full range of options to address integration issues can help to minimize VRE integration costs. Some analyses (IEA 2014) show that high shares (above 30 percent) of VRE could be achieved at modest additional overall electricity cost over time by explicitly planning for the best combination of VRE integration measures. Current modeling tools still have some limitations representing certain VRE characteristics, but they can still help identify future operational issues, simulate the mitigation effect of different solutions and operational strategies, and find the least cost option for the system through an iterative process.

In many cases, the flexibility of the overall power system will need to be increased as the share of VRE reaches higher levels. Flexibility can be provided through additional interconnections to give systems operators access to a wider pool of demand and supply options; by implementing demand response measures to provide flexibility in demand; through optimizing and adding flexibility in supply, such as can be provided by NG-fired generation technologies; and/or through incorporating energy storage to act as additional demand through charging when there is excess energy, as well as additional supply through discharging when demand exceeds generation capacity, as needed.

The value of flexibility in the system should be recognized through policy and regulation, and remuneration mechanisms for flexible capacity should be defined. For the most part, flexibility requirements should be technology agnostic in the absence of a strong reason to use a specific technology. The close link between scale-up of VRE and natural gas-fired power generation in many countries may lead to additional gas supply flexibility requirements. Policy-makers, planners, and system operators must coordinate closely to achieve security of gas and electricity supplies.

ENDNOTES

[1] Small coal-fired plants offer a more flexible dispatching for a power system operator than large coal power plants, but are less efficient and have higher emissions.

1

INTRODUCTION

At the end of 2013 installed renewable power capacity worldwide stood at 1560 GW, of which 560 GW was non-hydro technologies, including 318 GW of wind and 139 GW of solar photovoltaic (REN21).[2] In addition, total solar hot water capacity reached 326 GW. Countries pursue the development of renewable energy for a variety of reasons as summarized in Box 1.1.

Among renewable energy sources, solar and wind resources stand out as having high inherent resource variability and uncertainty. For these reasons, solar—photovoltaic (PV) and concentrated solar power

BOX 1.1

Drivers for the Development of Renewable Energy Technologies

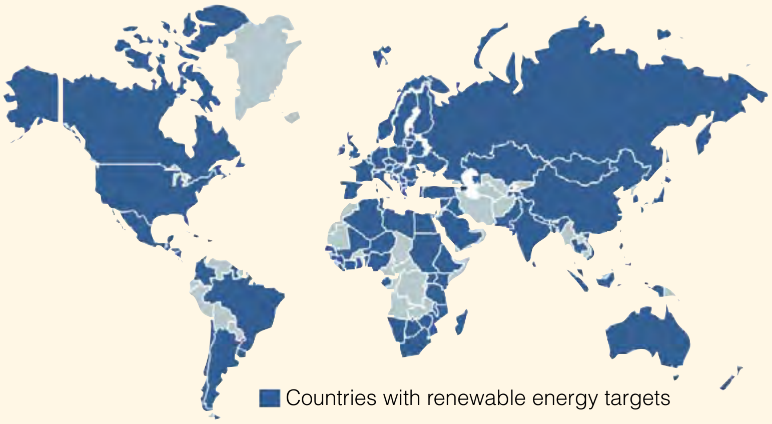
Countries pursue RE development for a variety of reasons:

- **Increased Energy Security.** Renewable assets are insulated from the volatility (in terms of price and availability) of fossil fuels. An increased share of renewable energy in the electricity generation mix can have an important stabilizing effect in countries where the power sector is heavily dependent on fossil fuel imports.
- **Domestic Environmental Benefits.** The combustion of fossil fuels in the electricity sector is responsible for air pollutants (CO, CO_2, ozone, NOx, SOx, suspended particulates, lead, volatile organic compounds, mercury, etc.) that can have an acute impact on human health, including respiratory, neurological, and cardiovascular diseases. Most renewable energy technologies have significantly lower domestic air quality impacts.
- **Global Environmental Benefits.** According to the Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report (2014), continued greenhouse gas (GHG) emissions at or above current rates would cause further warming and long-lasting changes in all components of the climate system, increasing the likelihood of severe, pervasive, and irreversible impacts on people and ecosystems. Switching from fossil fuels to renewable energy is an important component of efforts to limit climate change risks.
- **Increased Energy Access.** Many renewable energy technologies are modular, relatively quick to deploy, and suitable for grid connected and off-grid rural applications, allowing communities with no or very limited infrastructure to benefit from power supply.
- **Industrialization and Job Creation.** Countries see substantial entrepreneurial opportunities in the renewable energy sector that can help to create jobs, diversify revenue streams, build technical capacity, and stimulate new technological developments.
- **Affordability.** Renewable energy technologies are already cost competitive in countries heavily dependent on diesel imports, such as some small island development states. Moreover, a recent report (WEC & BNEF, 2013) has compared the actual costs (levelized cost of energy or LCOE) without subsidies of different generation technologies in a number of countries and found that the cost of wind and solar are already very close to fossil fuels in many markets.

Source | Adapted by authors from Madrigal and Porter (2013), IPCC, WEC and BNEF (2013), IEA (2011a), NRDC, IEC (2012), and other sources.

FIGURE 1.1

Countries with Renewable Energy Targets



Source | *REN21.*

(CSP) without storage—and wind generation technologies are often referred to as **variable renewable energy (VRE)**.[3] Ten years ago, VRE technologies appealed primarily to those willing to pay a premium to move away from fossil fuels for environmental reasons. Today, largely due to equipment cost reductions, VRE is becoming competitive even without accounting for positive externalities (REN21), putting the possibility of achieving high shares of VRE within reach in a growing number of countries.[4]

In less than a decade, the number of countries that have set renewable energy targets has more than tripled from 45 in 2005 to 144 at the end of 2013 (Figure 1.1). More than 100 countries—many of which are developing or emerging economies—have already enacted some kind of policy or mechanism to incentivize the development of renewable energy technologies (REN21). Many of those targets include ambitious levels of VRE.

The variability and uncertainty associated with VRE generation pose challenges regarding the reliability and stability of power systems that aim to produce a large share of their electricity with these sources. This in turn raises concerns about the "integration costs" defined as the "additional cost of the design and operation of the power system when VRE is added to the generation mix" (Ackermann 2012).

FOCUS ON FLEXIBILITY

A recent study (IEA 2014) shows that if appropriate measures are taken to address VRE integration issues, it is possible to integrate high levels of VRE (above 30 percent) at a modest incremental cost. To achieve this, power system planning, regulatory frameworks, and policy measures will need to be undertaken with the objective of minimizing total system costs rather than minimizing VRE generation costs alone. A comprehensive planning process would make use of advance modeling to evaluate the impact of VRE on the power system, optimize siting and timing of new VRE to minimize integration issues, and evaluate the progressive introduction of a suite of measures available to facilitate successful VRE integration into the power systems. Potential solutions include upgrading and adjusting operational procedures, VRE generation forecasting, investments in additional transmission and distribution capacity (including interconnections), diversifying the VRE technology mix, increasing geographic dispersion, and increasing the flexibility of the power system as VRE share rises.

Flexibility can be provided by options that act on the supply side (i.e., conventional and renewable energy generation technologies that can adjust the level of power output quickly and frequently), on the demand side (i.e., by making adjustments to the demand, for example through smart grid technologies and/or demand response management), or on both supply and demand using storage technologies. Flexible generation and demand response can quickly adjust power supply and demand, respectively, to compensate for changes in VRE output. Storage can shift generation or load as necessary to fill the gap between VRE generation and demand.

This report introduces the nature of VRE and the challenges associated with the integration of VRE technologies into a power system. It provides a brief overview of the suite of measures to limit and manage these challenges. The report then highlights the importance of increased flexibility when integrating high levels of VRE, and focuses on two options to provide flexibility: natural gas-fired power generation technologies and energy storage.[5] Finally, the report provides some insight into the implications for planning and regulation, and finishes with some recommendations for planners and policy-makers.

ENDNOTES

[2] Solar PV capacity installed (39 GW) accounted for 32 percent of all new renewable power capacity installed in 2013, surpassing wind installations worldwide (35 GW) for the first year ever (Renewables Status Report 2014).

[3] In the literature, other renewables such as hydropower or biomass are sometimes considered VRE, as they may demonstrate seasonal variability. Ocean energy (tidal, current, and wave energy) is also considered VRE, but has experienced limited deployment up to now. This paper focuses on wind and solar technologies as VRE, since variability patterns for wind and solar are more challenging to manage by power system operators.

[4] Ninety-eight percent of the existing PV capacity today was installed after 2004, and 50% was completed after 2012 (cleantechnica.com, June 7 2014).

[5] There are other ways to increase a power system's flexibility, including other generation resources (e.g., reservoir hydro) and demand response measures, that would deserve additional analysis.

2

INTEGRATING VARIABLE RENEWABLE ENERGY INTO POWER GRIDS: CHALLENGES AND SOLUTIONS

CHARACTERISTICS OF VRE GENERATION

VRE generation is variable, with limited predictability, and the resource is site specific. These characteristics lead to a number of challenges in terms of integrating VRE into the grid. The source of energy to be converted to electricity varies over time in a non-controllable way (from fractions of a second to hours or days). This results in a forecast error of the power output from VRE power plants. While there have been significant advances in wind and solar forecasting with important benefits in managing variability, the limited predictability of wind and solar resources remains a challenge in integrating high levels of VRE into a power grid. In addition, the resources are specific to the location. Wind speeds vary with terrain and weather patterns. The siting of a wind power plant and even the siting of the individual wind turbines within a wind power plant are based on site-specific mapping, measuring, and detailed modeling. Solar insolation also varies with latitude, environmental factors (amount of dust or air pollution, shading from nearby structures or natural features), and weather patterns.

Variability

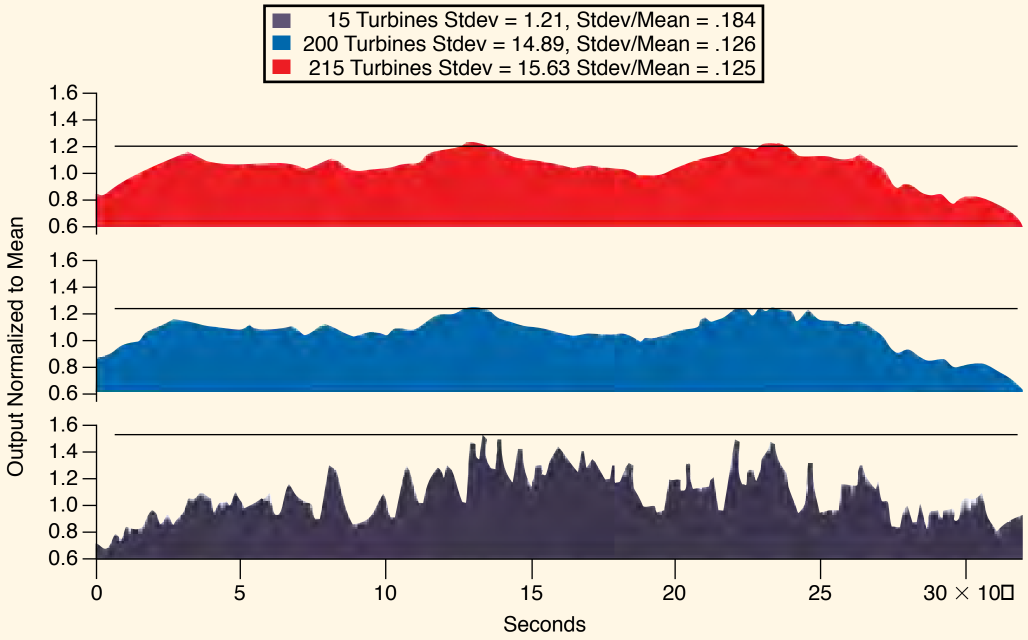
Wind power variability. The electrical output of wind turbines varies with the fluctuating wind speed at all characteristic timescales relevant for power system planning and operations (i.e., fractions of a second to years). On the positive side, wind has high potential for geographic dispersion (i.e., siting wind power plants in widely separated geographic locations) so that wind patterns determining the power output of one wind power plant are independent of those from a distant wind power plant. This helps to reduce the aggregated variability, as the output of the turbines becomes “less correlated” (Figure 2.1).

Despite the positive effect of aggregation, wind can stop blowing in a large area within a short period of time, causing rapid reductions in power output. In Denmark, the aggregated wind capacity dropped 90 percent (2,000 MW) over 6 hours in January 2005 (IEEE 2009). In February 2007, 1,500 MW were lost within 2 hours in Texas (IEEE 2009), and in 2009 Germany faced the challenge of coping with a change of 30 GW within a few hours (Euroelectric 2011). Conversely, a weather event could also suddenly increase generation output, requiring the curtailment of a large number of wind turbines. The probability of this type of event is low, but the impact on operations is highly challenging.

Solar power variability. There are two types of grid-tied solar power technologies: PV and CSP. PV makes use of semiconductors for the direct conversion of sunlight to electricity. Therefore, PV electrical generation changes nearly instantaneously with changes in solar radiation. Individual solar plants can have extreme variability on cloudy days. In general, the larger the footprint of the power plant and the larger the geographic dispersion between sites, the lower the combined variability will be (Figure 2.2). This is one advantage of distributed PV generation compared with a centralized PV power plant. The degree to which the variability is reduced depends on both the type of technology and the prevailing weather patterns.

FIGURE 2.1

Effect of Wind Aggregation on Variability



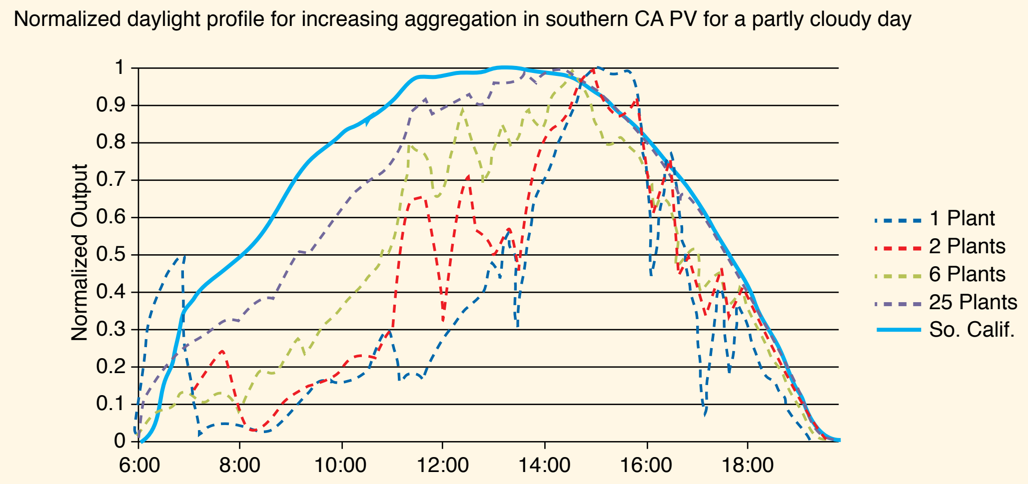
Source | *NREL.*

Commercially available CSP technologies reflect and concentrate the sunlight onto a receiver, where the heat transfer fluid (HTF) is heated. This heat is transferred to water in a heat exchanger, and the steam generated is used to drive a stream turbine and produce electricity. CSP benefits from the working fluid's thermal inertia[6] that allows CSP to have slightly lower intra-hour variability than PV (depending on the specific CSP technology and whether or not the design incorporates gas as auxiliary fuel during transient cloud conditions). It also delays the generation start-up at sunrise and delivers power for some additional minutes after sunset, compared with PV. The thermal inertia of the working fluid can be exploited further by incorporating additional thermal energy storage (TES), usually using tanks of molten salts, in the CSP plant design,[7] which increases a CSP power plant's capacity factor. Most of the CSP power plants currently under development incorporate some TES that charges entirely from the solar field and it is used to generate steam when required by the operator. Therefore, CSP with storage is not usually considered VRE, since TES can eliminate short-term variability and shift generation towards peak demand times, appearing to the operator as a conventional thermal plant.

A mix of VRE technologies within a balancing area can have important advantages in terms of reducing the variability of the overall VRE contribution, depending on the weather conditions and if those lead

FIGURE 2.2

Comparison of Photovoltaic Power Production Variability in Southern California, USA

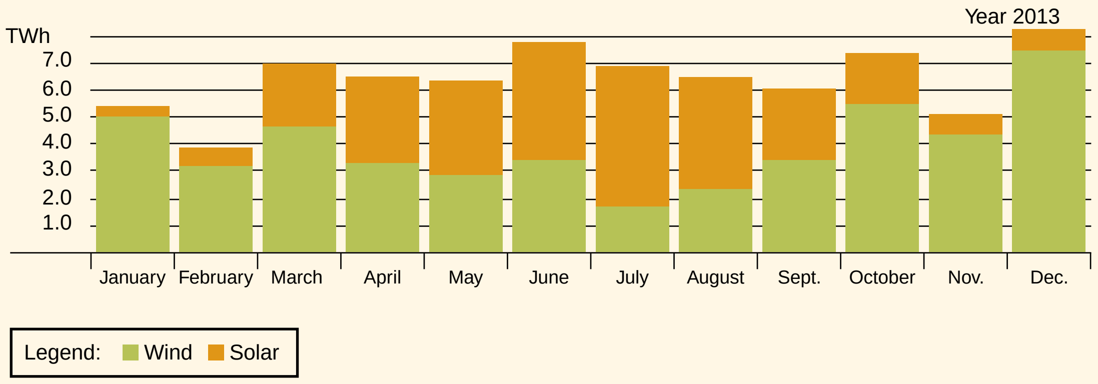


Source | *NREL.*

to complementary generation patterns. As an example, a recent report by the Fraunhofer Institute (ISE 2013) shows that high solar irradiance and high wind speeds tend to be negatively correlated in time in Germany. As a result, the combined monthly aggregated generation of the 35 GW of PV and 32 GW of wind capacity installed is less variable than wind and solar outputs separately (Figure 2.3).

FIGURE 2.3

Monthly Solar Photovoltaic and Wind Power Production, Germany (2013)



Source | *ISE, 2013.*

Limited Predictability

The predictability of VRE can be measured by different forecasting errors. Mean absolute error (MAE) and root mean squared error (RMSE) are the most widely used.

Wind power predictability. Today, it is possible to predict the generation of individual wind power plants one or two hours ahead with mean absolute errors (MAE) below 5 percent of rated wind capacity (Milligan, 2013; Ackermann, 2012). It is more difficult to predict generation a day ahead (MAE is usually between 10 and 20 percent of rated power) and the complexity of the terrain plays an important role in the performance of the forecast models. Wind power plants in highly complex terrains have shown day-ahead errors as high as 35 percent (IEC). Wind energy output forecast errors decrease with increasing numbers of wind turbines and larger geographic dispersion. In the state of Minnesota, US, the day-ahead MAE was reduced from 20 to 12 percent with the aggregation of the output of only four sites. For a larger geographical area like Germany, day-ahead MAE can be lower than 5 percent. In most countries with high shares of VRE, wind forecasts have improved significantly as a result of targeted research and development (R&D) efforts over the last decade (refer to Annex 1 for more information on forecasting).

Solar power predictability. PV generation variability associated with sunrise and sunset is predictable. In fixed-tilt installations, the shape of the PV output profile depends on the orientation of the PV panels. The orientation of the panels is fixed, while the position of the sun changes during the course of the day and the seasons. The orientation of the panels determines the power output and the time of the daily peak. The output of PV plants with tracking systems—which adjust the orientation of each panel during the course of the day and the year to maximize power output—shows more rapid ramp ups and downs at the start and end of day compared to those that use fixed-tilt panels.

However, the effect of clouds or sand storms is difficult to anticipate. Solar forecasting is not yet as developed as wind forecasting, but the rapid growth of PV deployment (both utility scale and small distributed systems) is driving several countries to coordinate R&D programs to enhance solar forecasting.[8]

Site-Specific

The technical feasibility of VRE depends fundamentally on the quality of wind or solar resources at a specific site. Therefore, unlike conventional power plants, the geographic location of VRE generators is often determined by the availability of enough resources to ensure relatively high energy yield. In many cases, the good VRE sites are located in remote areas, far from existing transmission infrastructure, demanding adequate transmission planning and policy decisions about who should bear the cost of the required transmission interconnections and potential system-wide upgrades. In the case of wind, off-shore wind turbines can perform at higher capacity factors than on-shore wind power plants, but transmission costs are higher since off-shore power plants necessitate the use of high-voltage, high-capacity submarine cables.

For solar, site resource dependency is more pronounced in the case of large wind or CSP projects than for PV technology, which is able to produce energy even at low levels of irradiation, though at higher cost. CSP plants are technically and economically feasible only in locations with high direct normal insulation (DNI).

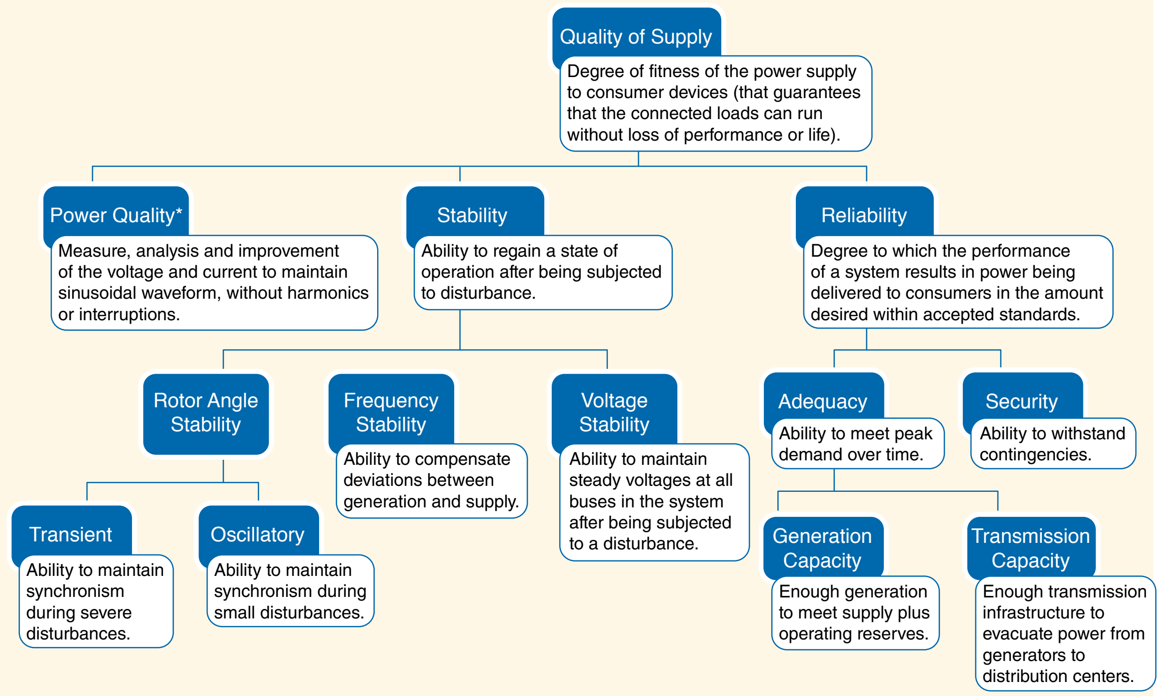
POWER SYSTEM OPERATOR RESPONSIBILITIES

Power system operators must balance supply and demand continuously to maintain high levels of reliability and stability, and ensure acceptable quality of power supply. Figure 2.4 shows the definitions of reliability and stability of a power system, and how both contribute to the quality of the power supplied to the consumers.

To achieve the required grid performance, operators need to have access to ancillary services to support the transmission of energy from generators to loads. Ancillary services include operating reserves, reactive power (to provide voltage support, i.e., increase voltage when needed), and black start (to restart the power system in case of a cascading black-out) (SNL). In practice, this means that operators hold generators in reserve to cover unexpected surges in demand and to cover loss of supply due to faults, planned outages, or reduction in output from VRE. Load and supply must

FIGURE 2.4

Stability and Reliability as the Pillars of Quality of Supply



Quality of Supply
Degree of fitness of the power supply to consumer devices (that guarantees that the connected loads can run without loss of performance or life).

Power Quality*
Measure, analysis and improvement of the voltage and current to maintain sinusoidal waveform, without harmonics or interruptions.

Stability
Ability to regain a state of operation after being subjected to disturbance.

Reliability
Degree to which the performance of a system results in power being delivered to consumers in the amount desired within accepted standards.

Rotor Angle Stability

Frequency Stability
Ability to compensate deviations between generation and supply.

Voltage Stability
Ability to maintain steady voltages at all buses in the system after being subjected to a disturbance.

Adequacy
Ability to meet peak demand over time.

Security
Ability to withstand contingencies.

Transient
Ability to maintain synchronism during severe disturbances.

Oscillatory
Ability to maintain synchronism during small disturbances.

Generation Capacity
Enough generation to meet supply plus operating reserves.

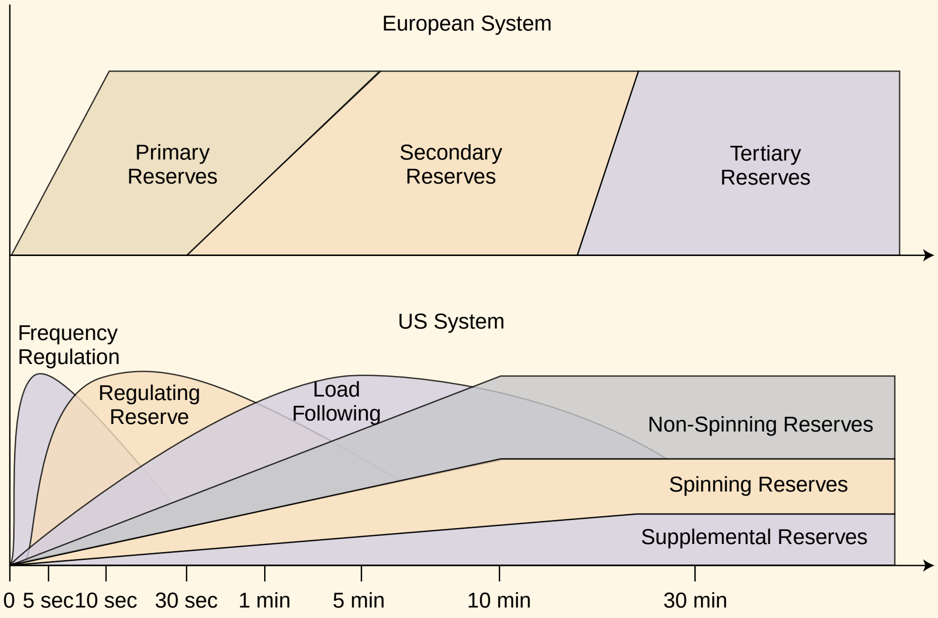
Transmission Capacity
Enough transmission infrastructure to evacuate power from generators to distribution centers.

**There is no standard definition of power quality; this definition was adapted from Fuchs and Masoum (2011).*

Source | Adapted by authors from Definition and Classification of Power System Stability IEEE/CIGRE Joint Task Force on Stability Terms and Definitions and DIGSILENT presentation on "Power System Stability on Island Networks & Power Quality in Power Systems and Electrical Machines" (Fuchs and Masoum 2011).

FIGURE 2.5

Comparison of European and US Operating Reserves Terminology



Source | Adapted by RAP (2013) from Ruggero Schleicher-Tappeser diagram based on NERC (2011) and Amprion (2013).

be balanced at all times to avoid frequency deviations that may lead to forced load-shedding (i.e., power outage for one or more areas). The generating capacity committed to this purpose constitutes the operating reserves of a power system. The ratio between the generation capacity installed and the peak demand is the operating margin. Typically, operating reserves should be at least equal to the capacity of the largest generator, plus a fraction of the peak load. However, the optimal operating margin for a system is dependent on a number of factors, including the size of the power system, the reliability level[9] required, and the costs related to the operating reserve power plants.[10]

The speed of response to the operator signal from the operating reserves is also very important. In fact, a fraction of the operating reserves is comprised of "spinning reserves," generators that are kept online, running at part load, in order to respond fast enough to the operator's dispatch instructions, since ramp up and down rates are much faster than start-ups and shutdowns.

Note that the nomenclature of the characteristic timescales and associated operating reserves varies depending on the country. Figure 2.5 shows a comparison between European and US[11] terminology with definitions provided in the Glossary.

CHALLENGES FOR POWER SYSTEM OPERATORS AND PLANNERS

At low levels of VRE penetration (generally below 5 or 10 percent, depending on the specific characteristics of the system), the variability and forecast error of the net load (total demand for electricity minus the demand served by VRE) are dominated by the more predictable variability in power demand. In such cases, power systems can usually accommodate the integration of small amounts of VRE, using the existing operating reserves, by adjusting operating procedures. As the share of VRE increases, the variability and uncertainty exceed the level typically covered by existing operating reserves, and additional measures are needed.

The VRE integration challenges for grid operators and planners are due to both the inherent characteristics of VRE resources (i.e., variable, with limited predictability and site specific) and the characteristics of the system into which they need to be integrated. VRE integration challenges and costs will depend on the existing flexible resources and the quality of power supply required. In systems where consumers require high reliability and power quality, power system operators may need to spend additional resources to minimize the potential imbalances or disturbances introduced by VRE, since the cost of loss of load or damage to equipment (both leading to loss of production) would be high (Sims 2011).

The following sections summarize the main challenges. Figure 2.6 shows a simplified summary of the main impacts that high shares of VRE can have on power system operations, highlighting the range of timescales at which the variability may be experienced.

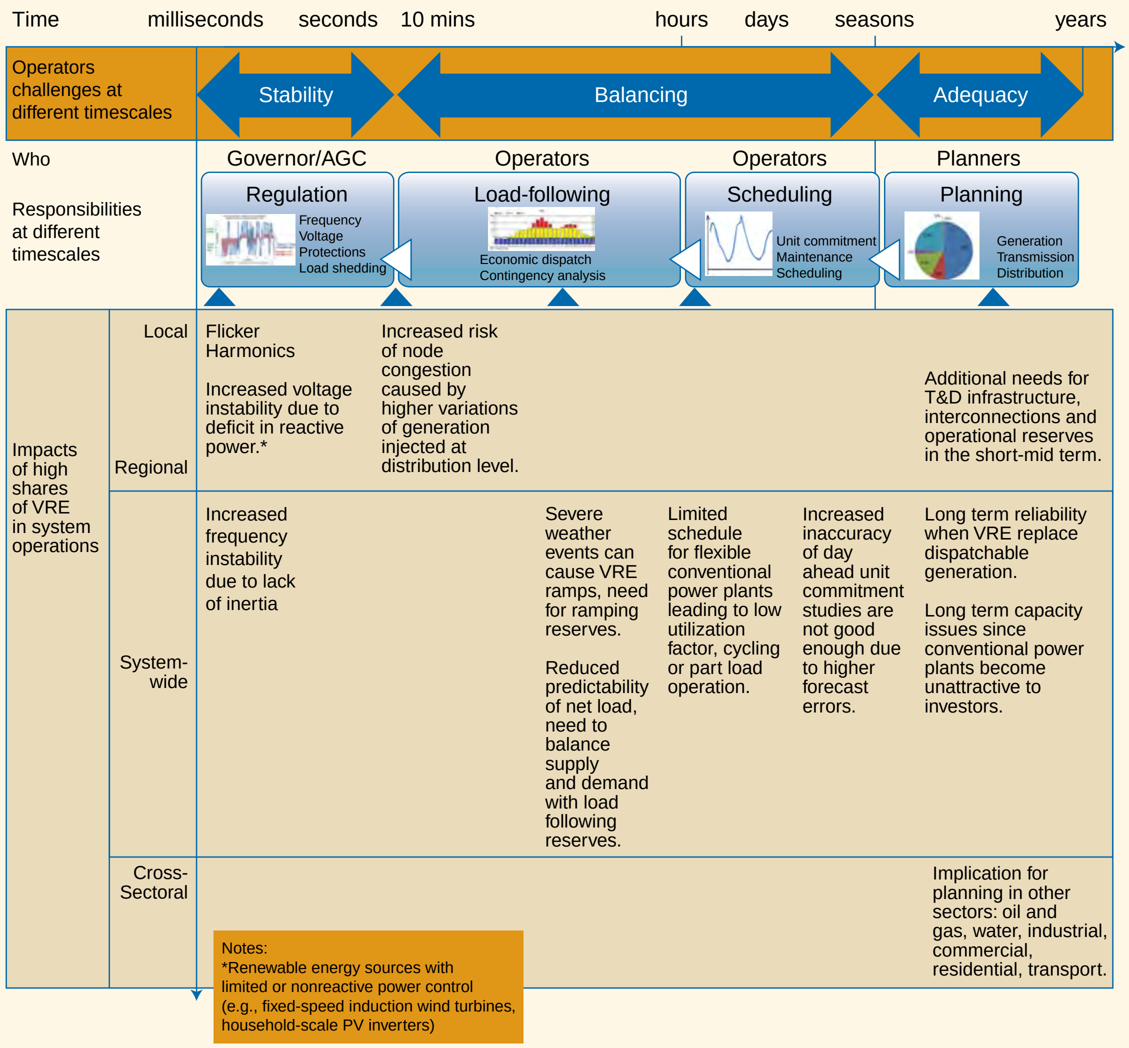
Planning

Generation and transmission adequacy. Peak availability for VRE resources can often occur during periods of relatively low demand for electricity, leading to the risk of over-generation at high shares of VRE. The reverse can also occur: VRE output may not be available during peak demand times. Ensuring that there is sufficient capacity available to meet peak demand over time (i.e., fulfilling the adequacy criteria; see Figure 2.3), taking into account an increasing share of VRE is an important challenge in system planning.

The site-specific nature of VRE resources is also a factor to be included in planning for system adequacy, particularly transmission adequacy. The best sites in terms of wind or solar resources may be far from the main consumption centers and existing power lines. For example, only 7 percent of the US population resides in the 10 states with the highest wind potential (NERC 2009). One of the main challenges for the development and integration of VRE into a power system is to properly plan for transmission expansion to connect VRE power plants to the grid. Overall system expansion planning must take into account options for VRE power plant siting, recognizing that the best resource sites from the perspective of maximizing the output from an individual VRE power plant may not be the best from the point of view of connecting supply with sources of demand. Transmission and distribution limitations (e.g., bottlenecks, lack of financing, non-existent or unclear expansion regulation) may need

FIGURE 2.6

Potential Impact of High Shares of VRE on Power System Operations and Planning



Local / Regional:

Flicker
Harmonics

Increased voltage instability due to deficit in reactive power.*

Increased risk of node congestion caused by higher variations of generation injected at distribution level.

Additional needs for T&D infrastructure, interconnections and operational reserves in the short-mid term.

System-wide:

Increased frequency instability due to lack of inertia

Severe weather events can cause VRE ramps, need for ramping reserves.

Reduced predictability of net load, need to balance supply and demand with load following reserves.

Limited schedule for flexible conventional power plants leading to low utilization factor, cycling or part load operation.

Increased inaccuracy of day ahead unit commitment studies are not good enough due to higher forecast errors.

Long term reliability when VRE replace dispatchable generation.

Long term capacity issues since conventional power plants become unattractive to investors.

Cross-Sectoral:

Implication for planning in other sectors: oil and gas, water, industrial, commercial, residential, transport.

Notes:
*Renewable energy sources with limited or nonreactive power control (e.g., fixed-speed induction wind turbines, household-scale PV inverters)

Note | *Timescales and potential impacts are indicative only.*

Source | *Adapted from several sources by the authors.*

to be addressed. Therefore, characteristics of the demand (growth, variability, and correlation with VRE generation) must be considered in planning the best approaches to integrating VRE.

Planning for increased distributed VRE. One of the potential benefits of VRE is the possibility for distributed generation, such as rooftop PV systems, to feed into the distribution grid. Greater dispersion can help to limit aggregate variability as discussed above, as well as potentially reduce losses as the distance between power generation and use is shortened. These benefits have contributed to a growing trend in VRE distributed generation. However, distributed generation can pose some challenges that need to be managed. Distribution grids are traditionally designed as "passive" networks that transfer bulk power from transmission system to customers. If not properly managed, VRE generation connected to the distribution grid may cause short-circuiting behavior of components due to improper protections, high fault currents, or voltage fluctuations. These impacts can be technically solved with the use of adapted inverters or transformers,[12] but it will impact the system cost (IEA, 2014). If distributed VRE contribution is expected to be significant, the planning process may need to assess smart grid approaches (such as innovative voltage control and power flow management, dynamic circuit ratings, and demand response) that transform the distribution system from a passive to an "active" network. This would allow VRE distributed generation systems and consumers to work reliably as "virtual power plants" (Navigant 2014).

In addition to the operational issues posed by distributed generation, there is also a potential impact on the traditional "utility" model. In countries with increasing retail tariffs and VRE incentives (e.g., Germany, Australia, or some US states such as California), self-generation based on renewables has become an attractive proposition for electricity consumers, creating a new class of "prosumers"—efficient end users that meet part of their electricity needs with distributed generation. Utilities have lost the regular revenue that used to come from these prosumers, while still having to provide them a reliable service when the distributed power generation is insufficient to supply the prosumer's full demand. Additionally, the fixed and operations and maintenance (O&M) costs for the utility remain at the same levels or may even increase. Some experts envision an evolution of utilities towards a business model similar to the one used by mobile networks, with higher fixed charges and different service packages (Sioshansi & Jones 2014).

Scheduling and Load Following

Generation variability and limited predictability present challenges in terms of balancing or matching the power generation and power demand in the range from minutes to hours. From an operational point of view, the characteristics of the power output have implications for plant scheduling (i.e., advance notice in terms of hours or days for individual power plants to be committed to generate at a given output level), and load following (i.e., actually utilizing the generation from power plants to meet the load). To maintain the balance between generation and load, the system needs to be able to respond when VRE output changes (Figure 2.7). The response could involve drawing on energy storage devices, activating demand response options, or ensuring that some plants on the system, including VRE generators, are available and able to ramp up or down on the same timescales as the changes in VRE output. At high levels of VRE, generation variability leads to the need for greater flexibility in the rest of the system to allow economic dispatch, while the limited predictability of VRE output can potentially lead to the need for increased load following reserves to compensate for the increased uncertainty in the net load.

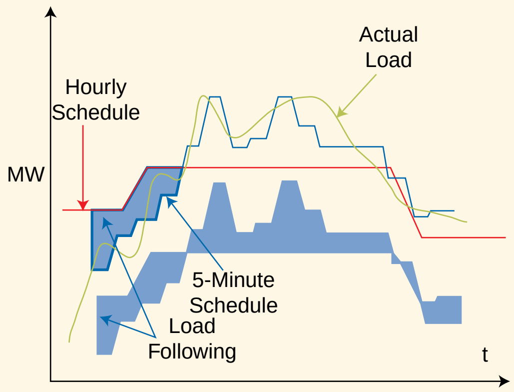
Regulation

Steady state stability.[13] **Instantaneous matching of supply and demand to maintain frequency.** From an operational point of view, VRE variability and relatively limited predictability lead to challenges in maintaining the overall stability of the power supply in terms of ensuring that actual, instantaneous power generated exactly matches actual, instantaneous power demand to avoid frequency deviations in the power system (Figure 2.6). In the timescales of milliseconds to minutes, frequency, voltage and rotor angle stability fluctuations (Figure 2.3) are usually managed by automatic control systems.[14] In modern systems,[15] signals are automatically sent to one or more generators to cause an increase or decrease in power output to match the changing load conditions and keep the frequency within specified limits.[16] The service provided by this process is called **regulation** (Figure 2.8). At very high shares of VRE, particularly PV, the automatic regulation reserves (i.e., a subset of the operating reserve capacity) need to be able to respond much faster, more frequently and within wider operation ranges to compensate for frequency deviations.

System dynamic stability. In addition to the stability issues linked to the short-term, unpredictable variations of VRE, there is also another indirect impact on stability at high penetration levels of

FIGURE 2.7

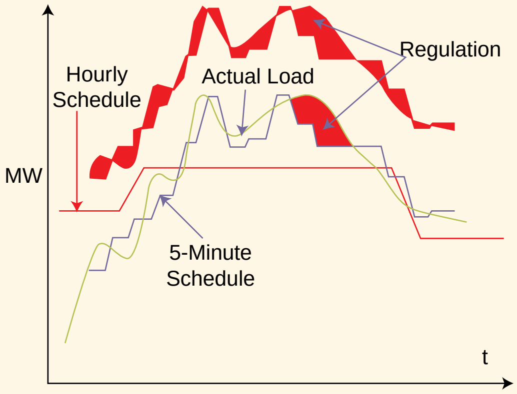
Balancing (Load Following) Requirement (blue)



Source | (CAISO & NERC, 2013).

FIGURE 2.8

Regulation Requirement (red)



Source | (CAISO & NERC, 2013).

VRE. A grid disturbance, such as the sudden loss of a large generator, may cause large frequency fluctuations. The rotating inertia[17] of the large rotating masses of conventional generators, such as in steam or gas turbines, helps to arrest fluctuations and stabilize system frequency following such a disturbance. Compared to conventional generation, VRE technologies have limited capability to provide the system with such "frequency response" services. PV solar generation offers no rotating inertia and, therefore, no frequency response. Some modern wind generation technologies are specifically designed to provide a frequency response,[18] though older designs generally do not have this capability. The displacement of conventional power generation that provides rotating inertia with low- or no-inertia VRE resources may raise stability issues as the VRE share increases. In general, this leads to greater rates of frequency change in the case of system contingencies (e.g., generating unit loss) or sudden load variations. Organizations like California ISO or CAISO (US) have analyzed this type of impact in their system and identified possible solutions (CAISO & NERC, 2013).

SUITE OF MEASURES FOR VRE INTEGRATION

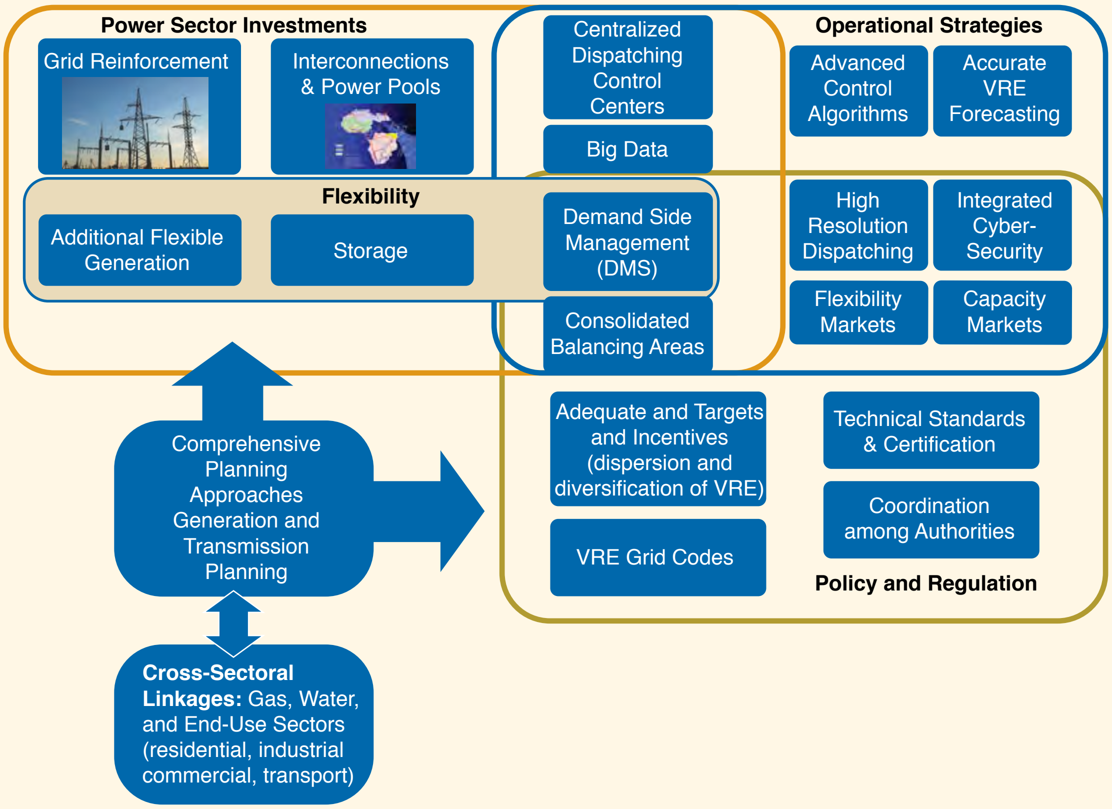
The set of the main measures available to reduce and manage variability and limited predictability introduced at higher levels of VRE is shown in Figure 2.9. Integrating high levels of VRE requires that investments, operational strategies, policy, and market solutions be designed in a coordinated way according to a comprehensive planning strategy that minimizes the overall power system cost.

The set of **operational measures** that can be employed in VRE integration in the short- or medium-term include:

- **Adjusting operating procedures to optimize the use of existing flexible generation**[19] (i.e., diesel engines, CT, CCGT, etc.), traditional storage (pumped hydro), and any other energy storage available to minimize integration cost. For example, the number of generators under automatic control can be increased, and the start-up and ramp-up times can, in some cases, be modified to provide additional operational flexibility.
- **Moving to advanced control technologies that can automatically manage the ramping up and down** and other adjustments needed, over very short timeframes, for frequency control using the various flexibility options available in the system. Making such adjustments manually is challenging, especially in terms of achieving economic dispatch of the flexibility options. As the variability and uncertainty of the net load increases with increased share of VRE, manual control becomes more difficult. In power systems moving to increased share of VRE, it is advisable to introduce automated control systems. In automatically controlled power systems, the number of dispatchable generators under automatic generation control (AGC) can be increased, and the control algorithms can be optimized to ensure adequate regulation while ensuring that dispatching is as economic as possible.
- **Introducing enhanced measurement** such as online real-time monitoring of weather variables (wind, pressure, radiation, temperature, humidity) and VRE output, **and state-of-the-art VRE resource forecasting** to help to reduce forecast errors. Prediction and forecast accuracy should

FIGURE 2.9

Main Measures to Reduce and Manage Generation Variability and Uncertainty at High Levels of VRE



Source | Adapted by authors from WB and other sources.

have economic incentive in the electricity market. Annex 1 provides additional information about state-of-the-art forecasting and its applications.

- **Combining centralized dispatching control centers with optimized high resolution dispatching and reduced balancing intervals.** For example, in Spain, the Centro de Control de Régimen Especial (CECRE) collects all information about the current variable generators, provides a centralized forecast service, and helps to make control decisions aimed to integrate the maximum VRE power at any given moment.[20] The CECRE is integrated into the Electrical control Center (CECOEL), that controls all electrical power production and transmission in the country. In addition, the reduction of scheduling intervals allows for more accurate VRE forecasts. Balancing energy transactions among different areas are typically scheduled on an hourly basis. The reduction of scheduling intervals to 10 minutes, for example, allows for more accurate forecasts of VRE generation, and dispatchable generators in an adjacent balancing area can be used to provide the necessary flexibility through an interconnection (NERC 2009).

- **Implementing VRE grid connection and operability standards (VRE grid codes).** Grid codes are used to define the electrical performance requirements of generating assets (mainly related to voltage and frequency), operational and dispatch rules, and the technical requirements for interconnection to the grid. Due to the particular characteristics of VRE, additional standards or amendments to the existing ones are critical to define aspects that may be especially important for VRE, such as fault-ride through capabilities,[21] the type of participation in frequency response, and the responsibility of VRE providers with regard to providing forecasting and any other key data needed by the grid operators and dispatch centers. If properly implemented, appropriate grid codes can considerably reduce potential adverse impacts of grid-integrated VRE. In fact, VRE can be part of the integration solution. Modern wind power plants are able to regulate and control the production upward or downward within seconds, depending on the availability of wind. For example, onshore wind turbines in Denmark are exposed to market signals, giving the operators the opportunity to react to negative prices in the market by reducing their production[22] (Stroom, Anderser, & Jones 2014).
- **Establishing a compensation mechanism for plants contributing to the adequacy and balancing of the power system** (e.g., remuneration schemes or, in the case of liberalized power systems, implementation of capacity and flexibility markets). Capacity markets can drive capacity investments in anticipation of future power needs. Flexibility markets provide remuneration to flexible generators able to provide additional operational reserves.
- **Importing and exporting power to neighboring zones,** when operational strategies cannot solve balancing or regulation problems in the balancing area without curtailing production of VRE, is usually the most convenient and cost effective measure to manage VRE variability (Ulbig, Andersson, and Jones). Consolidating balancing areas (which may require additional interconnections) can improve load diversity, reduce aggregate variability, and grant operators access to a deeper stack of generation and storage to balance net load. Increasing the size of the balancing area is effective to the extent that variability of generation and demand in some areas complements variability and demand in other areas. This tends to happen in systems that span across varied climatological and topological conditions that impact VRE availability and electricity demand (Madrigal and Porter 2013).

In the longer term, proper planning for VRE integration would involve:

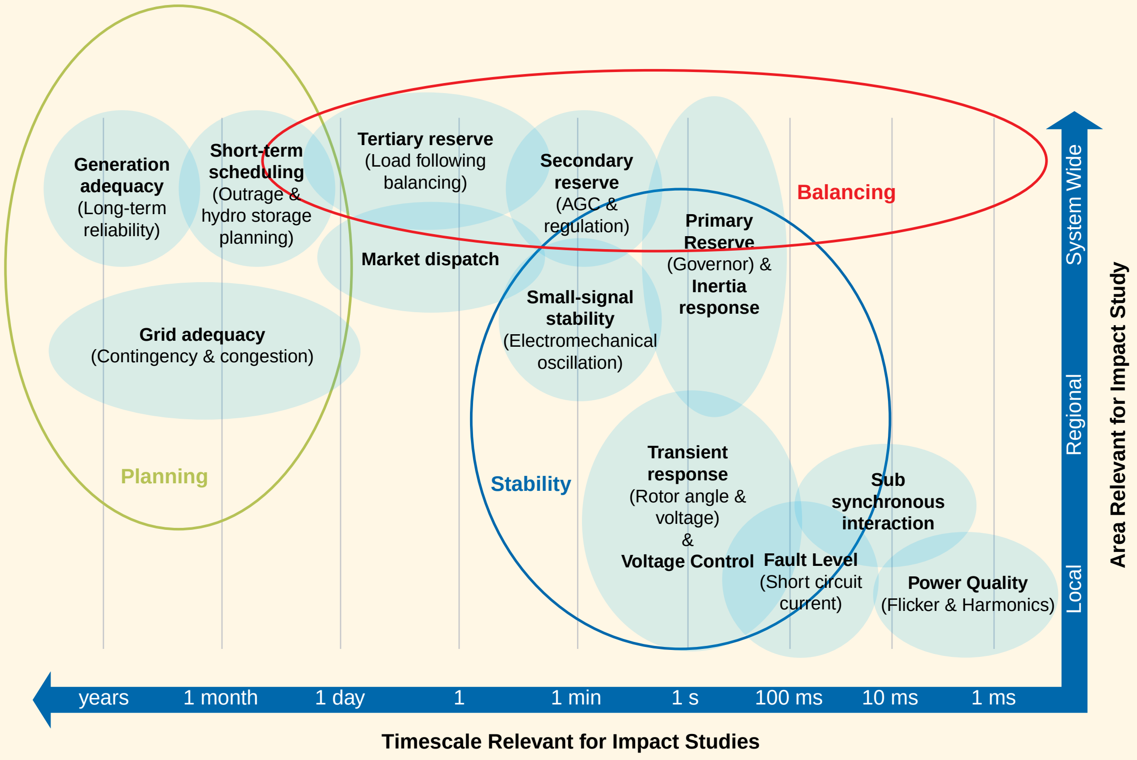
- **Siting VRE using criteria for best integration,** which may be different from sites that are best in terms of individual plant performance. For example, the proximity to transmission lines could be given a higher priority over the quality of the solar/wind resource when selecting sites for large projects, or selecting sites with relatively lower resource variability among the feasible ones, even if the project return on investments are lower than in other locations;

- **Setting VRE targets and the rate for VRE growth,** taking into consideration the timing of complementary generation and transmission systems investments;
- **Including a balanced mix of sources of VRE** when beneficial (i.e., when the generation patterns of solar and wind are not correlated, the combined use of both technologies tends to reduce the aggregated variability); and
- **Ensuring that the rest of the power system is as "VRE friendly"** as possible by consolidating balancing areas, creating new interconnections, and increasing the flexibility of the system.

Modeling can help operators and planners to analyze different scenarios for VRE integration. Figure 2.10 shows the multiple studies that are typically conducted to evaluate specific impacts of high levels of VRE on the power system at the different timescales (Australian-AID, WB, & ESMAP 2013).

FIGURE 2.10

Issues Assessed in Planning and Simulation VRE Integration Studies



Source | Adapted from Energynautics (Australian-AID, WB, & ESMAP, 2013).

Current modeling tools have some limitations with respect to representing VRE,[23] but can help to identify future operational issues and simulate the mitigation effect of different measures. Advanced planning methods aim to find the least cost VRE integration solution (set of measures) following an iterative process between the short-term impact simulations and the longer term planning models that yield energy production cost estimations.

Even with the right operational strategies and a geographically disbursed and diversified VRE capacity mix, additional flexibility is generally needed at high VRE penetration levels (above 15 to 20 percent, depending on the match between demand and VRE generation).[24] Flexibility can be increased on both the demand and supply sides. The following chapters discuss two options for adding supply side flexibility to a power system: natural gas-fired power generation and energy storage.

ENDNOTES

[6] The working fluid is usually oil that absorbs the heat concentrated by arrays of reflectors or “heliostats” and carries the heat to the steam generating unit where the heat is converted to steam to drive a steam turbine. The working fluid cools relatively slowly (thermal inertia). It remains hot for some time after the heat from the reflectors drops off (e.g., at nightfall or when clouds block the sun) and continues to transfer heat to the steam generating unit, dampening or eliminating the impact of short-term fluctuations in solar radiation.

[7] TES can be directly or indirectly integrated into the CSP plant design, depending on whether the technology is able to use molten salts as primary heat transfer fluid (HTF) or not. Parabolic trough CSP plants use oil as the primary HTF that can be transferred to the molten salts used in the TES with the use of a specially designed heat exchanger. New solar tower designs can achieve higher operating temperatures allowing the use of molten salts as primary HTF and direct integration of the TES in the plant design.

[8] Refer to Annex 1 for more details about VRE output forecasting.

[9] There are several parameters used to specify reliability levels, such as the loss of load hours (LOLH), loss of load event (LOLE), or the normalized expected unserved energy (EUE). Different standards define the desired reliability level that is used to compute the operating reserve margin.

[10] Above certain levels, additional reserve capacity may not improve reliability significantly and may become too expensive. However, in countries where the economic consequences of power cuts are much greater than paying a reliability premium, levels of 25 to 35 percent are considered reasonable, and countries like Philippines or Singapore have margins higher than 50 percent. Reserve margins are much tighter and even negative in many countries and regions, leading to highly unreliable service in some cases. Typically, 12 percent is considered a minimum operating margin in many systems without a significant share of VRE.

[11] The Union for Coordination of Transmission of Electricity (UCTE) and now the European Network of Transmission System Operators for Electricity (ENTSO-E) specify reserve requirements with different terms and criteria in Europe than those used by NERC in the United States (Kirby, Ela, and Milligan 2014).

[12] This is a common solution to voltage fluctuations experienced in rural areas with long distribution lines.

[13] Steady state stability of a power system is defined as the ability of the system to return to steady state after a small disturbance in the network.

[14] Automatic control systems include generator governor and excitation systems and Automatic Generation Control (AGC) for managing frequency, and power system stabilizers and Automatic Voltage Regulators (AVRs) to manage rotor angle stability and voltage fluctuations.

[15] In systems without AGC, one generating unit in a system is designated as the regulating unit and its generation is manually adjusted to control the balance between generation and load and maintain system frequency at the

desired value. The remaining units would be controlled to provide a share of the load according to their ratings. With automatic systems, many units in a system can participate in regulation, reducing the wear on a single unit's controls and improving overall system efficiency, stability, and economy.

[16] The limits vary with the country. In the United States, NERC requests generators over 10 MW to have governors that keep frequency levels within 0.037 Hz, for a 60 Hz system. The AGC action is guided by the Area Control Error (ACE), which is a function of system frequency and tie line flows.

[17] The synchronized rotation speed of the rotating masses that comprise turbines and generators determine the frequency of the power system. Turbines and synchronous generators store kinetic energy due to their large rotating masses, which constitute the "grid inertia." When a large power plant is lost, or the load increases, this kinetic energy is immediately released into the grid to supply the load. This, however, leads to a reduction of the rotation speed of the turbines and frequency in synchronous generators decreases. The turbine governor maintains the desired system frequency by adjusting the mechanical power output of the turbine and stabilizing the system. For example, in the case of a steam turbine, the mechanical output of the turbine can be modified by the governor by increasing or decreasing the amount of steam entering the turbine.

[18] More information about the contribution of modern wind turbines to frequency support can be found in Muljadi, Gevorgian, & Singh (2012).

[19] This may not always be possible for all flexible plants in the system. In some cases, the operation modes of generators may be specified or limited under power purchase agreements (PPAs) with independent power producers (IPPs).

[20] For more information, refer to http://www.ree.es/en/educaree/videos/cecre-control-centre.

[21] Older wind turbines technologies still in use are sensitive to voltage reductions (which require them to be disconnected from the grid), use induction generators that consume reactive power, and introduce additional voltage variations to the system. Newer technologies are able to cope with voltage drops and remain connected, and can mitigate the voltage variations in the system. In PV, voltage swing limits are imposed by the inverters, which, when exceeded, cause them to cease feeding the grid.

[22] The Danish incentive scheme for wind technology is structured as a premium on top-of-the-spot price to be paid during the first seven or eight years of generation. When spot market prices are negative, if wind turbine operators decide to curtail production during the subsidy period, the premium is still paid to them. In this way, wind turbine operators are not incentivized to maintain production during periods of over-generation and wind turbines participate in the balancing of the power system.

[23] In many cases, additional data about the operational characteristics of VRE systems are needed to create accurate power flow and stability models that adequately capture the impact of VRE technologies in the power system. Standard, non-confidential, non-proprietary VRE models are needed, particularly in the case of small VRE generators, which can have an important impact on the system at an aggregate level.

[24] Some countries have managed to integrate high levels of VRE with limited flexibility, thanks to interconnections to other countries where power could be consumed or stored.

3

NATURAL GAS AS A FACILITATOR FOR VRE INTEGRATION

NATURAL GAS-FIRED GENERATION AS A SOURCE OF FLEXIBILITY

Most natural gas-fired generation technologies can provide flexibility. Unlike coal or nuclear, natural gas can be utilized for a number of centralized or distributed flexible generation technologies in a wide variety of capacity ranges that can contribute to VRE integration. Natural gas-fueled assets can run in different operating modes, from peak to base-load, in stand-alone or standby applications, or even combined with VRE systems in hybrid power plants.

Certain types of gas-fired power generation technologies are better suited at select capacity ranges than others (Annex 2). Three key characteristics of interest in the context of VRE integration are: the **turn-down ratio** (minimum load as a percentage of the rated capacity at which a generator can be reliably operated); the **start-up rate** (time from starting up a generator to running at full rated capacity),[25] and the **ramp rates** (rate at which a power plant can increase or decrease output once in operation, usually expressed as megawatts or percent of load per minute). The term "**cycling**" refers to the process of repeated turn-down, part-load operation, shutting down, and starting up of a power plant. Annex 2 provides a summary of the key characteristics of gas-fueled power generation technologies.

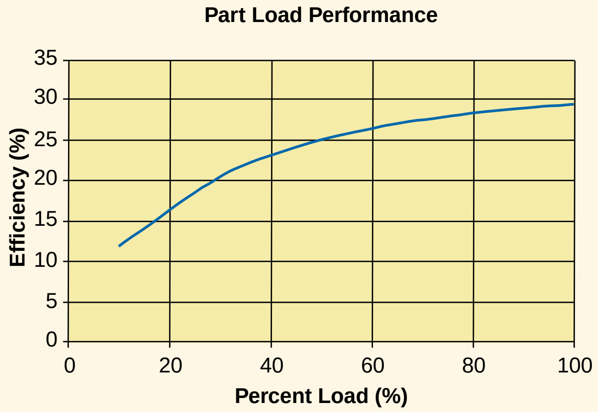
At the system level, NG-fired generation can add flexibility and can contribute to addressing some of the issues associated with VRE integration during scheduling, dispatching, and regulation. Fast start-up time and ramp rates are highly desirable when operating with VRE. Whereas coal or nuclear steam cycle generators can take more than 12 hours to reach full load, some gas combustion technologies have start-up times measured in minutes. Start-up and ramp rates for gas generation systems vary with technology and installed capacity. These characteristics may be the deciding factor in selecting the appropriate technology, depending on the flexibility needs of the system.

Some natural gas-fired generation technologies are designed to be flexible and can provide operating reserves needed to correct imbalances during dispatching and regulation. Operating reserve plants are not expected to run at high capacity factors but need to be able to start-up, then ramp up and down very quickly, as well as have low turn-down ratios to ensure they can work at reduced output at the request of the operator. Efficiency, while still important, is less of a consideration as these plants are not intended to operate for long periods.

Simple cycle gas turbines, also called open cycle gas turbines (OCGTs), and gas-fired reciprocating engines[26] are the technologies most commonly selected as operating reserve plants. When less than full power is required from a gas turbine, the output is reduced by lowering the turbine inlet temperature. This change in operating conditions also reduces efficiency and increases emissions per unit generated, especially at half load and below. Figure 3.1 shows a typical part load performance curve for an OCGT.

FIGURE 3.1

Typical Open Cycle Gas Turbine Part Load Performance



Source | EPA 2008 from EEA/ICF.

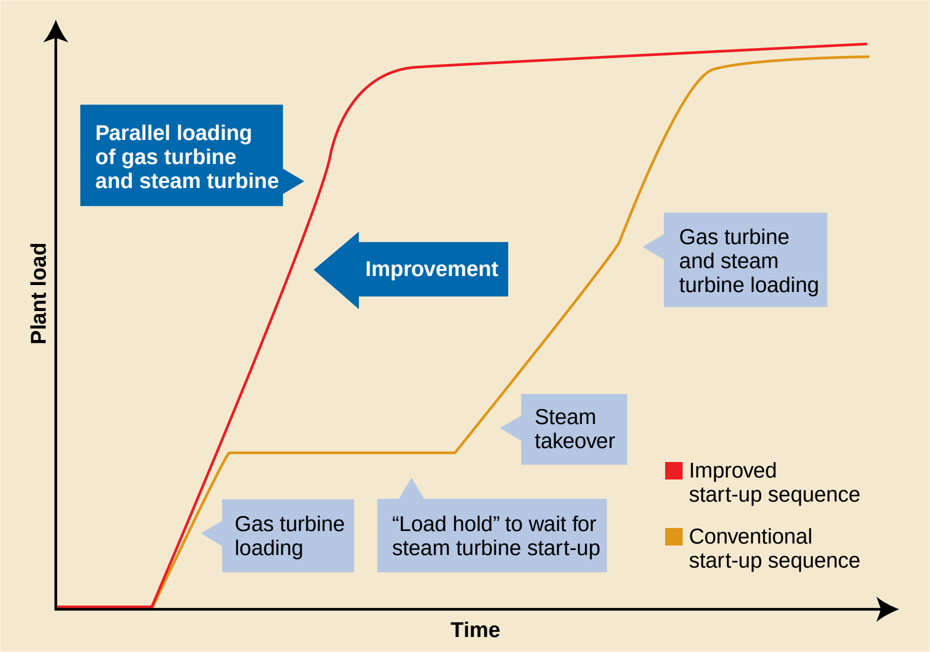
In simple cycle, start-up times for gas turbines are about 10 to 15 minutes in "hot-start" conditions.[27] Gas reciprocating engines can start and ramp to full load more quickly due to rapid ignition of fuel within the cylinders and the coordinated starting of multiple generating sets. Some reciprocating engine manufacturers state that their engines reach full load in as little as 2 minutes under hot start conditions and 7 to 12 minutes under cold start conditions (Wärtsilä). This makes them suitable to work as fast-response, non-spinning reserves, since they do not need to be operating at part load in order to respond within 10 minutes of the operator signal.

Natural gas-fired power plants designed as base-load and mid-merit plants can provide some system flexibility. **Combined cycle gas turbine (CCGT)** power plants are the most common natural gas option for base-load and mid-merit, due to their capacity range, high efficiency at full load and low levelized cost of electricity (LCOE). Typical CCGT start-up rates and turn-down ratios offer greater flexibility than other thermal base-load/mid-merit technologies (such as nuclear or coal-fired).

New, fast-acting CCGTs are being designed to achieve faster cycling and feature short start-up times compared to standard CCGTs, through a design that allows starting up the steam turbine in parallel with the gas turbine (Figure 3.2). Fast CCGT power plants can achieve full load output in less than 40 minutes compared to 100 to 150 minutes for hot start-up of conventional CCGT plants. Two major manufacturers, General Electric (GE Flex Efficiency 50 Combined Cycle Plant) and Siemens (FACY), are at the forefront in the design and implementation of combined cycle power plants with fast ramp up. Figure 3.3 shows a start-up time comparison of the Wärtsilä 34SG and 50SG power plants with simple cycle and combined cycle gas turbine plants from manufacturers GE, Alstom, and Siemens.

FIGURE 3.2

Comparison of Start-up Rates in CCGT: Conventional vs. New Fast-Response Designs



Source | Siemens Energy (SIEMENS).

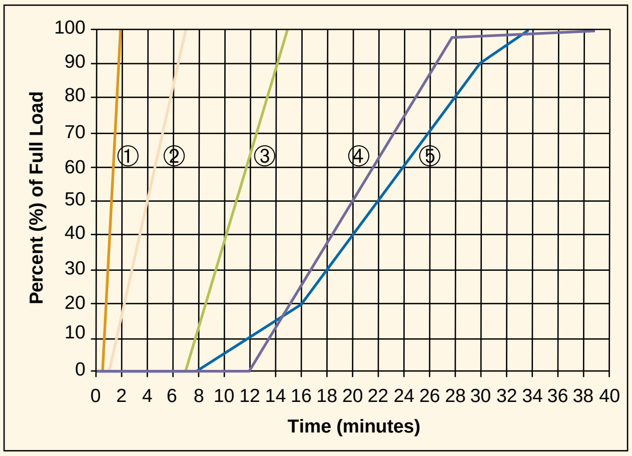
One approach to providing a relatively high level of flexibility while also minimizing emissions during operations for the overall system is to install a combination of micro-turbines, reciprocating engines, simple cycle gas turbines, and CCGTs with different rated capacities. To avoid operating gas turbines and CCGTs at part load (and reduced efficiency), micro-turbines and reciprocating engines can be dispatched when the net load is relatively small, operating near design capacity. When the load increases, the larger gas turbines and CCGTs can be brought online (NOVI 2012).

LIMITATIONS OF GAS-FIRED GENERATION IN SUPPORTING VRE

Experience in countries with both high VRE and gas-fired power generation has shown that, from a technical perspective, the flexibility provided by gas-fired generation technologies has facilitated high levels of VRE penetration while maintaining quality of supply (reliability, stability, and power quality; see Figure 1.1). The flexibility of the non-VRE generation is particularly important for power systems with limited interconnections.

FIGURE 3.3

Comparison of Hot Start-up Rates among Different Natural Gas Technologies



① Wärtsilä 34SG power plant under hot start condition: 70˚C cooling water temp; prelubrication of engine and gen bearings

② Wärtsilä 50SG power plant under hot start condition: 70˚C cooling water temp; prelubrication of engine and gen bearings

③ Simple cycle industrial (heavy duty) gas turbine under hot start conditions: GE, Alstom

④ GE FlexEfficiency CCGT under hot start conditions: purge credit; Rapid Response; startup within 8 hours of shutdown

⑤ Siemens F-class CCGT under hot start conditions: auxiliary steam, stack dampers maintain HRSG temperature and pressure

Source | *Wärtsilä*

However, gas-fired power generation assets have inherent operational limitations in terms of the level of flexibility that can be provided and this may impact their ability to address the full range of variability issues presented by VRE integration. The limitations include:

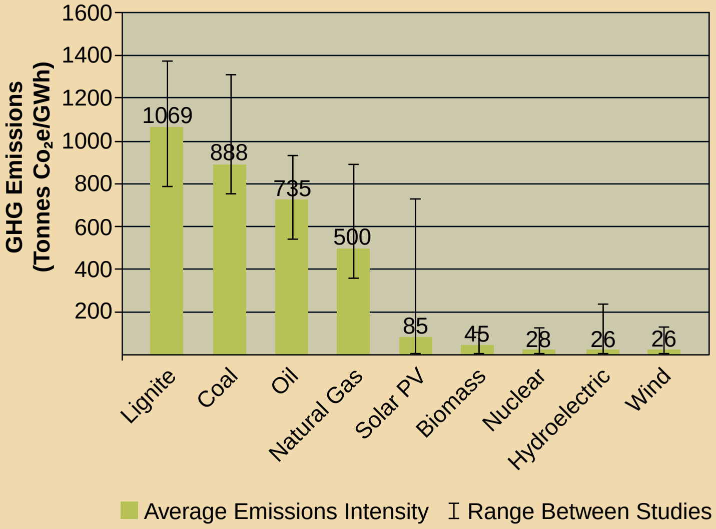
- **Operating ranges and characteristics.** While better than most thermal alternatives, the turn-down ratios of most gas technologies, except micro-turbines, are limited to 40 or 50 percent of full load, as shown in Annex 2. There are also limitations on the start-up and ramp rates. The characteristics of the variability introduced by VRE may require alternative or additional sources of flexibility. Despite their relatively fast start-up and ramp rates compared with other conventional options, very fast and sudden variation of net load (i.e., at timescales below the ramp up/down rates) cannot be balanced with gas-based technologies and may require other flexibility options, such as electrical storage or demand response.

BOX 3.1

Impact of Part Loading on Emissions

Natural gas has higher energy content and lower carbon and other environmental emissions per kWh of electricity generated than other fossil fuels such as coal, diesel, or heavy fuel oil. When comparing the lifecycle emissions for the most relevant energy sources,* the GHG emissions are calculated for the power generation process. For natural gas, the emissions are shown for a CCGT plant working at design efficiency (i.e., base-load operation).

CO_2 Lifecycle Emissions Comparison**



Source | *World Nuclear Association 2011.*

However, when gas power plants designed for base-load/mid-merit generation are used to provide flexibility and operate for substantial periods at part load, GHG emissions and other pollutants per kWh can increase considerably with respect to the design conditions. This impact should be taken into account when considering the global environmental benefit of high levels of VRE with flexibility provided by natural gas generation. Reciprocating engines exhibit approximately 5 percent increase in GHG emissions per unit of output when their load is reduced to 50 percent; combustion turbines and micro-turbines exhibit approximately 20 percent increase in GHG emissions per unit when their load is reduced to 50 percent.

**Different studies can show important variations in LCE estimates. Technical harmonization of key performance parameters and primary energy resource characteristics is required in order to ensure consistent values that reflect a modern reference system. For more information about the LCE harmonization, refer to: www.nrel.gov/harmonization and http://www.nrel.gov/docs/fy13osti/57187.pdf.*

***The emissions in the figure do not include any gas leakage that may occur during natural gas extraction or transportation.*

Source | *NOVI Energy.*

- **O&M costs, efficiency, and emissions.** Part loading and frequent cycling of a gas engine or turbine results in more wear on mechanical components, requiring more frequent maintenance and increased operating cost. Part load operation also reduces efficiency, causing increased emissions per unit of energy generated. For example, compared to full load, the efficiency of gas turbines is reduced by about 9 to 12 percent at 75 percent load and by 20 to 25 percent at 50 percent load. Efficiency deteriorates at a much faster rate below 50 percent and there is a lower limit (turn-down ratio) at which the machine can be operated without surpassing emissions-specified limits and reducing the equipment lifetime (NOVI 2012; Eurelectric 2011).

CCGTs, except the new fast-combined cycle power plants, are designed to operate as base-load or as mid-merit generation due to their high efficiency. Open cycle gas turbine plants and gas reciprocating engine power plants are commonly used as peaking units, where a relatively low capacity factor is assumed as the basis for the expected returns on investments. However, as the VRE share increases, experience shows that most natural gas generators, including CCGTs, are expected to work as load-following generators (i.e., responding to changes in renewable energy output), reducing output or shutting down when net demand is low to avoid over generation, and restarting when demand is high. The implications of this dynamic are discussed in Chapter 5. Box 3.1 describes the effects of part load running on emissions.

ENDNOTES

[25] Comparison of different technologies and designs is complicated by the way start-up time is measured by different manufacturers. Depending on the manufacturer, the start-up time can be considered from push of the start command or from ignition. In the case of gas turbines, this difference in “start” definition can be as much as 20 minutes. It is also important to differentiate between the time to achieve full load versus partial load (Wärtsilä n.d.).

[26] Fuel oil-fueled reciprocating engines have similar characteristics; many reciprocating engines are dual fuel.

[27] To meet “hot start” conditions, cooling water is preheated and maintained above 70°C, engine bearings and generator bearings are lubricated, and the engine is turning slowly. GTs undergo a sequence of increasing compressor spin to reach firing speed, ignition, turbine acceleration, synchronization, and loading.

4

STORAGE AS A FACILITATOR FOR VRE INTEGRATION

STORAGE TECHNOLOGY OPTIONS

Energy storage comprises a wide range of technologies with a corresponding range of performance capabilities that can address different issues associated with VRE integration. Uniquely among flexibility options, storage can provide “load leveling” or “load shifting” by acting as a source of demand (through charging) at times of low demand and a source of supply when demand increases or other sources of supply reduce output (discharging).

Some of the key performance metrics for storage are included in Table 4.1.

TABLE 4.1

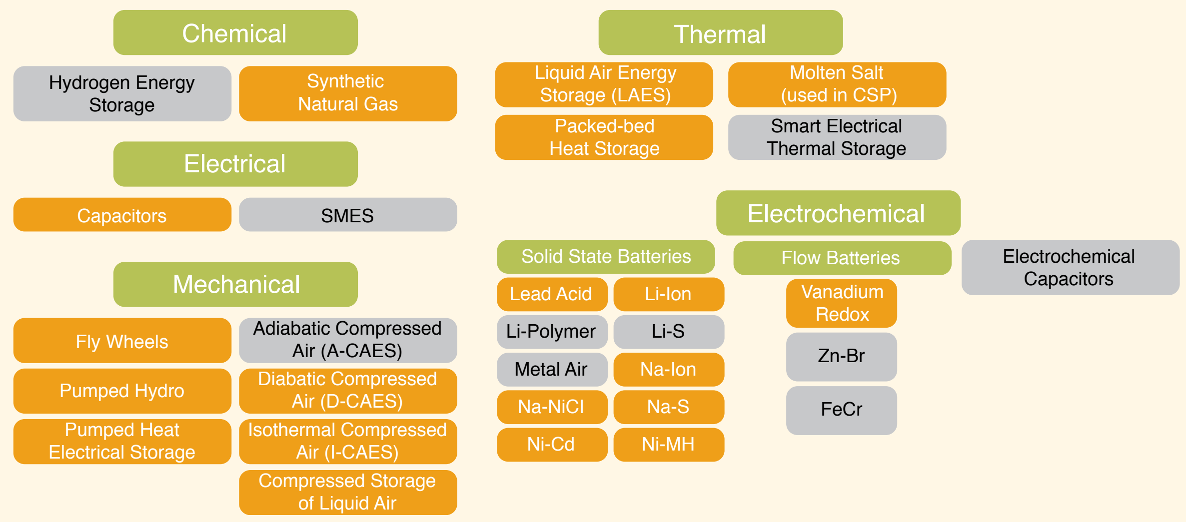
Energy Storage Performance Metrics

METRIC	DEFINITION
Size (kW of kWh)	Characterized in terms of: Power capacity or power rating (MW): Instantaneous energy available from the storage system Rated power is defined as the power that can be sustained for the rated duration of response Energy rating (MWh): Total amount of energy that a storage can store or discharge from its full state
Storage Time or Duration of Response (secs thru hrs)	Time during which a storage device can maintain output at a rated power Characterizes the duration of response of a storage device
Efficiency or Round Trip Efficiency (%)	Input to output energy ratio, i.e., amount of energy that can be discharged from a storage system relative to the amount of energy that was put in. This accounts for the energy lost due to mechanical, electrochemical, or electronic losses. Typical values: 60–95% Characterizes how much energy a device consumes in order to provide the required services
Response Time (seconds)	Time in with which a storage device can go from standby mode to full output Requirements for response times vary with applications
Energy Density (kWh/ton-metric)	Maximum energy that a storage device can accumulate per unit of mass Determines how large of a footprint the technology needs to store a given amount of energy or offer a certain capacity
Specific Energy (kWh/m^3)	Maximum energy that a storage device can accumulate per unit of volume Determines the space needed to accommodate the device
Depth of Discharge (%)	Power that a storage device provides to a given application during one cycle of discharge Measured as a percentage of power discharged relative to full capacity, tends to decrease with time for some technologies
Discharge Time	Time required by a storage device to release its stored energy. Depending on the characteristic discharge time, storage systems can be divided in short, medium, or long discharge time devices
Cycle Durability (number of cycles)	Number of cycles a storage technology can withstand at a certain depth of discharge before performance declines
Ramp Rate (%/seconds)	Rate at which storage power can be varied
Energy Retention	Amount of time that a storage system retains its charge. Some storage devices tend to dissipate energy while not in use (stand-by losses)

Source | Adapted by authors from KEMA, DOE, SNL and other sources.

FIGURE 4.1

Commercial and Pre-Commercial Storage Technologies



Note | *Technologies marked in orange are considered more mature and commercially available. Those in grey are still under development or early/pre-commercial stage.*

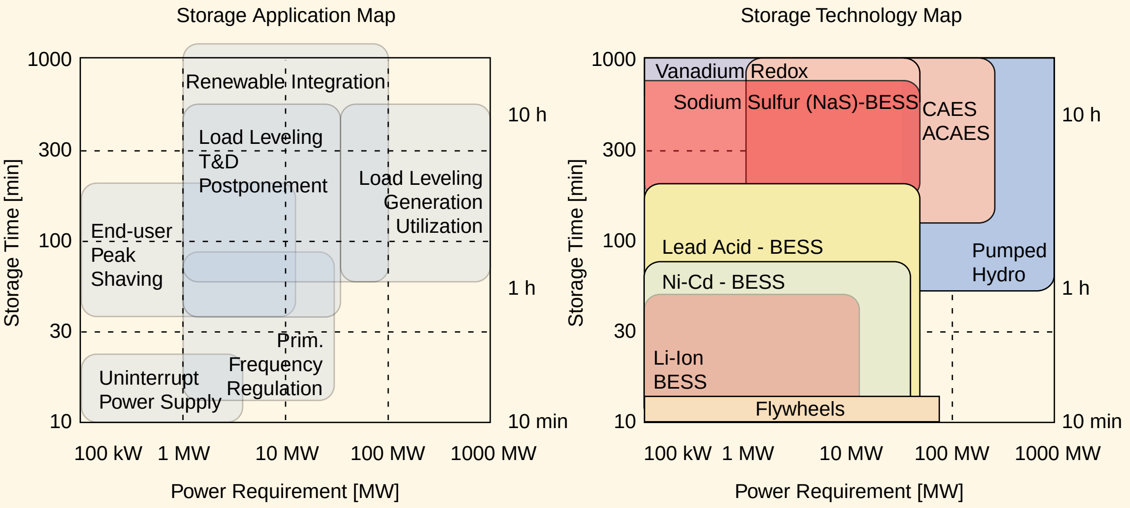
Source | *Adapted from European Association for Storage of Energy (EASE) and Energy Storage Association (ESA).*

Commercial and pre-commercial storage technologies. Some storage technologies, such as pumped hydropower, have been part of power systems for decades. Compressed air energy storage (CAES) and lead acid batteries have also been used for many years in power systems applications. Newer technologies, now in the early market adoption stages, such as flywheels, lithium-ion batteries, and sodium sulfur batteries (NaS), offer a wider range and improved performance capabilities. Others, such as flow batteries, superconducting magnetic energy storage devices (SMES) and nano-capacitors, are still in the pre-commercial development stage. Figure 4.1 shows the range of storage technologies available commercially and at the pre-commercial stage. Technologies marked in red are considered commercial; the rest are in R&D or demonstration stages.

Chemical energy storage uses electric energy to create fuels—synthetic methane, synthetic gas, and hydrogen—that are subsequently burned in conventional power plants also known as "power-to-gas technologies." These projects are still in the demonstration stage, with Germany leading the research. Audi opened a 6-MW power-to-gas facility in June 2013.

Thermal energy storage refers to storage technologies where energy is stored as thermal energy, or 'heat.' This can be in the form of sensible heat (hot water tanks or ice), latent heat (where the storage medium stores and releases energy by changing phase), or thermochemical heat (where thermal energy is absorbed or released via a chemical reaction). Thermal energy technologies are

FIGURE 4.2
Map of Storage Technologies and Their Applications



Source | *Smith, Sen, and Kroposki 2008.*

most effective when used in situations where the end usage is thermal energy, as in heating or air conditioning, or when the energy supply is a thermal source, as in CSP.

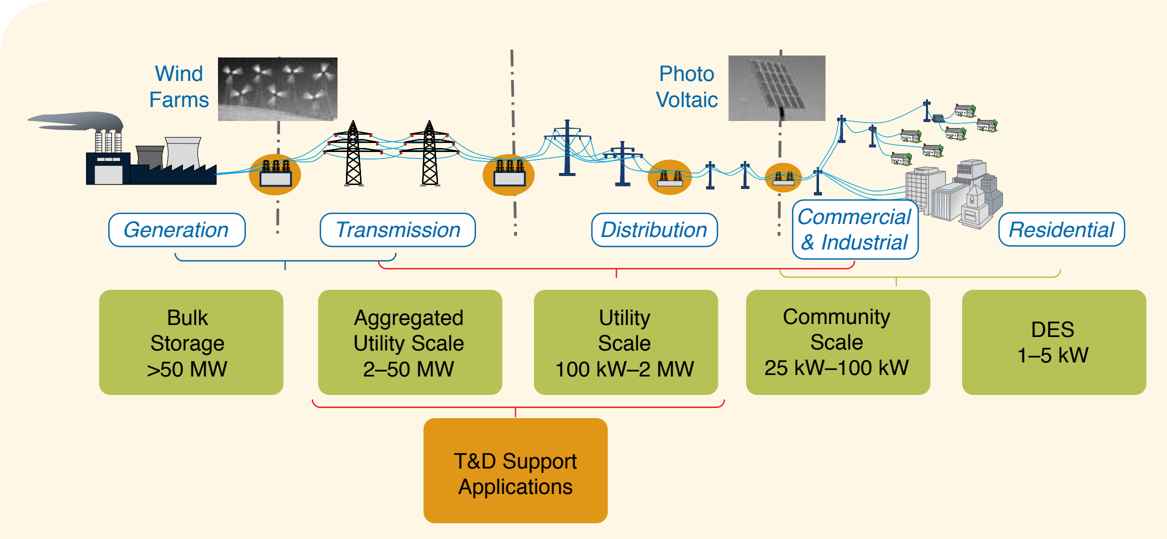
Electrochemical energy storage technologies (batteries) convert electricity to chemical potential for storage and then back again.

Figure 4.2 includes a comparative chart with characteristics of the most common commercial or near-commercial storage technologies and the types of applications for which they may be suitable. Annex 3 provides further information on their characteristics, as well as a brief description of their operating principles and some examples of storage facilities currently in operation.

Storage technologies provide a range of flexibility options. Energy storage has the potential to serve many functions across the power delivery value chain, and may be connected at various locations along the electric grid system—ranging from distributed energy storage (DES) at the household scale to bulk grid storage on the order of 50 MWs and above. Each grid service (balancing, stability regulation, power quality, back-up supply, etc.) has its own performance requirements for storage capacity, duration of discharge, response time, etc., that, in addition to cost factors, determine whether an energy storage technology is suitable for a given application. Response time and storage time—also called duration of response—together with storage capacity are critical parameters in determining what role a particular storage technology could have in VRE integration.

FIGURE 4.3

Energy Storage Participation along the Power Supply Chain



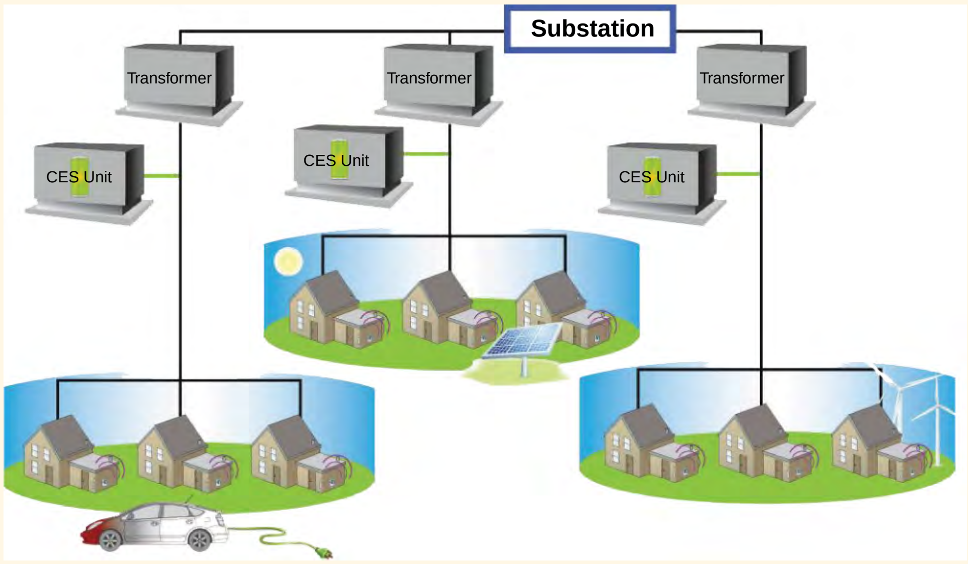
Source | *Adapted from KEMA.*

Potential contribution of the main commercial storage technologies to VRE integration at different points along the electricity grid. Figure 4.3 summarizes the different capacity ranges of storage that are relevant at different points along the electricity grid power supply chain.

Bulk storage. At utility scale, storage has been mostly used to take advantage of the electricity price difference between peak and off-peak hours by purchasing and storing energy when electricity price is low and selling it back to the grid when the price is higher. This is referred to as energy shifting. Pumped storage, combined heat and power (CHP) plants with thermal storage, and, to a lesser extent, CAES have been used for decades for energy shifting applications. Pre-commercial technologies such as NaS and flow batteries are also well suited for energy shifting.

Transmission and distribution support. Storage applications paired with transmission and distribution (T&D) support applications (such as frequency and voltage support or contingency reserves[28]) can also help with the integration of VRE. Utility-scale storage sited at a transmission substation (ranging from 2 to 50 MW, such as a lead acid battery bank) can be used to relieve congestion in the transmission system that may be caused by over installation of VRE in a specific area. That is, if the power output from a VRE power plant at a particular time temporarily exceeds the capacity at the local substation or transmission lines, the excess can be stored and discharged into the system when the power flow through that section of the grid is reduced. Storage at a distribution substation may range in size from 100 kW to 2 MW. For example, energy storage can defer the need to upgrade or facilitate achieving the optimum timing of distribution upgrades by relieving feeder lines that are close to maximum capacity during peak solar supply from distributed PV generators (KEMA 2012).

FIGURE 4.4
Community Energy Storage



Source | Adapted from PJM.

Community energy storage. The relatively new concept of community energy storage (CES) allows the utility to serve a cluster of customers by siting utility-owned energy storage systems close to the end of the distribution line. Distributing the storage instead of using one or a few larger units can have significant benefits. CES units (batteries) range from 10 to 100 kW and can help integrate VRE at the local level while maintaining reliability. CES provides the ability to control power flows at the local and system levels and provides additional flexibility that larger, centralized units might not provide (PJM 2013; ESA; see Figure 4.4). Besides, it is unlikely that a significant amount of CES units be out of service at any time.

Distributed energy storage. Distributed energy storage (DES) is the term used for small storage systems at the household level. DES may play a very important role in the future in combination with small VRE systems (particularly PV) and automated demand response technologies (refer to Annex 2). With several hours of discharge capacity, DES can help to firm up the generation of small household systems. A recent report from Rocky Mountain Institute (2014) concludes that PV-plus-battery grid parity is coming soon for a growing number of customers in the United States. In the future where smart grids become more wide spread, electric vehicles (EV) are also expected to play an important role in DES. With advanced controls such as would be introduced in smart grids, the battery storage capacity in a large number of electric vehicles could be aggregated and deployed as one or several distributed energy storage resources. Pilot programs are under way in many areas[29] where price, demand, or other signals are used to shift EV charging to low demand periods, or to periods with high VRE production that may otherwise not be utilized if demand is not high enough. Charging of EVs can be either turned on and off (load shifting) or the rate of charging can be increased or decreased (load modulating). If fully leveraged, a growing EV fleet can provide an additional tool for integrating VRE generation into the grid, but, even in advanced power markets, the full scale realization would likely take some time. For that to happen, the interfaces between the "storage owners" and system operators will require additional regulation (EUC 2011).[30]

BENEFITS OF COMMERCIAL STORAGE TECHNOLOGIES AT DIFFERENT TIMESCALES

Planning. All storage technologies can contribute to meet system capacity and improve reliability in the long run, but bulk storage technologies (pumped hydropower, CAES, CSP-TES, and NaS) are likely to have a more important contribution to generation adequacy and transmission capacity[31] in the long run due to the higher capacity.

Scheduling and Load Following. Storage has two important roles to play in the context of scheduling and load following. First, the ability of storage technologies to provide load shifting, i.e., charging storage with large amounts of low-cost, off-peak renewable energy (e.g., produced by wind turbines at night) and discharging during peak demand to displace high-cost on-peak energy generation, offers a large potential value and significant flexibility in the context of scheduling. Pumped hydro, CAES, and the thermal storage used in CSP plants are used to shift load. The second role is in load following, which involves ramping power output up or down to compensate for changes in the net load. Technologies such as pumped hydro and CAES can be used for load following. Other storage options such as Na-Ni-Cl batteries can provide a frequent and faster response to sudden variation in the net load, though with lower energy storage capacity. Both, storage for load shifting and storage for load following are often labeled as VRE integration storage applications, since the most important issues created by high levels of VRE occur at scheduling and real-time dispatching timescales as discussed earlier in "Challenges for Grid Operators and Planners" (Chapter 2).

Regulation. Storage can also provide grid operational support and transmission and distribution support services that can help minimize VRE impacts on regulation. Some storage technologies can respond at the timescales needed to assist with regulation (Box 4.2). Several studies (KEMA 2012) have shown that storage is more effective than combustion turbines in providing regulation services. A storage system can range from –1 to 1 MW (charging and discharging) whereas a combustion turbine can only go from 0 to 1 MW. If the storage system is inverter based,[32] it can go from one extreme to the other in a just a second or two, supplying regulation almost instantly compared to the 30 to 60 seconds required by a combustion turbine to achieve full output. Flywheels, Lithium-ion (see Figure 4.2), and lead acid batteries, together with capacitors, are currently offer the most suitable regulation services. These options respond in milliseconds and have high cycle lives.

Power quality. Power quality issues such as harmonics[33] or voltage drops can be aggravated by the use of some VRE technologies, such as older wind turbines.[34] These quality issues can be addressed by injecting power at the feeder or distribution level. Storage technologies with response times on the

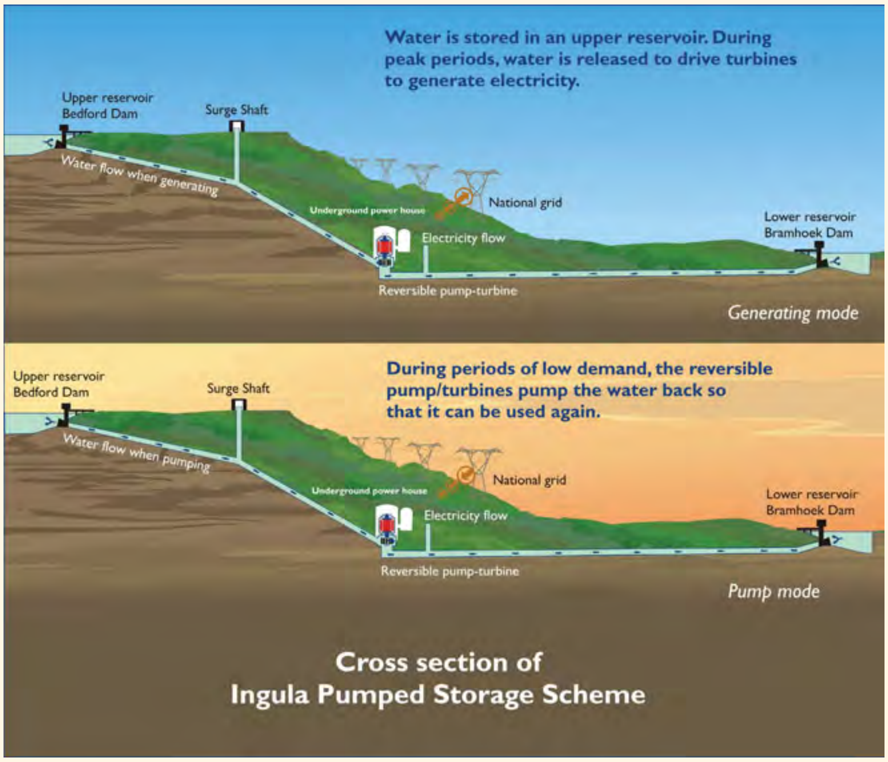
BOX 4.1

Ingula Pumped Storage Facility, South Africa

Eskom initiated a study on appropriate sites for pumped storage schemes in the 1980's. In 1988, Palmiet—a 400-MW storage facility—was commissioned in the Western Cape region. The latest pumped storage facility—Ingula—will incorporate four 333-MW reversible pump turbines and is scheduled to come online in 2014. Although there are two other pumped storage schemes are already operating, Ingula will be the largest hydroelectric power source in South Africa.

A pumped storage facility needs suitable dam sites relatively close together but at a significant altitudinal difference, suitable geology, and available water. The Ingula Pumped Storage Scheme consists of an upper and a lower dam; both of approximately 22 million cubic meters water capacity. The dams, 4.6 km apart, are connected by underground waterways through an underground powerhouse, which house the four 333-MW pump turbines. During times of peak energy consumption, water will be released from the upper dam through the pump turbines to the lower dam to generate electricity. During times of low energy demand, the pump turbines are used to pump the water from the lower dam back to the upper dam.

The final selection of the Ingula site is north east of Van Reenen's Pass, spanning the escarpment of the Little Drakensberg, straddling the provincial boundary of Free State and KwaZulu (between Lesotho, Swaziland, Johannesburg, and Durban). Additionally, the Ingula Pumped Storage Project will be operating in a region where there are currently no wind turbines installed, but with a good wind potential.



Source | *ESKOM Ingula Visitor Center.*

BOX 4.2

Laurel Mountain, West Virginia (AES Energy Storage)

In operation since 2011, the Lithium-ion battery storage plant of Laurel Mountain, located in West Virginia (US) is the largest in the world with 32 MW of power capability. The plant includes 16 battery containers, 8 inverter containers and chillers, and provides fast-response for frequency regulation and wind generation balancing in PJM Interconnection's (a regional transmission organization) wholesale market.

Illustration of a Li-Ion Battery Installation

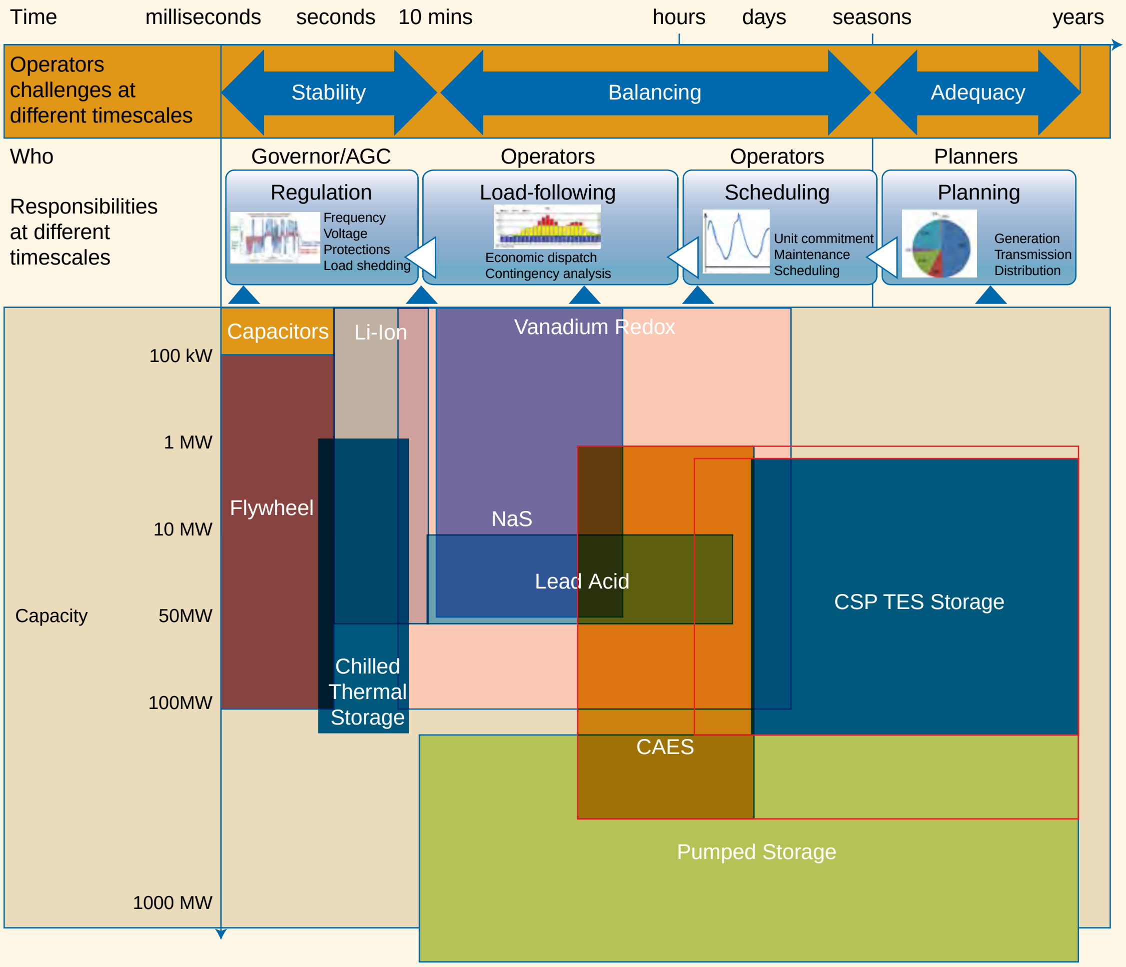
Source | AES Energy Storage.

order of milliseconds, such as capacitors or batteries (e.g., Lithium-ion or lead acid batteries), can be used to help with power quality.

Figure 4.5 shows the potential contribution to VRE integration of the main commercial storage technologies at the different power system operational timeframes. While all storage technologies should be accounted for planning purposes, the figure shows the options with higher capacity can have a more important contribution to adequacy in the long term.

FIGURE 4.5

Potential Contribution of the Main Commercial Storage Technologies to VRE Integration at Different Timescales



Source | *Adapted by authors from several sources.*

LIMITATIONS OF STORAGE FOR SUPPORTING VRE

High costs. From the technical capability point of view, the wide range of storage technologies available can contribute to solving most VRE integration challenges at the different timescales, from power quality and regulation to dispatching/load following issues. However, despite the promising prospects mentioned above, the current cost of energy storage technologies continues to be the most important barrier to its wide scale deployment.

BOX 4.3

Impact of Energy Storage on GHG Emissions

In general, the use of storage in systems with high shares of VRE can lead to a reduction of GHG emissions for the system for two reasons. First, the bulk of the energy stored would be VRE, and therefore, even the energy loss during the charge/discharge would be renewable energy with limited or no associated CO_2 emissions. Second, by reducing or replacing the use of NG-fired or fuel oil-based generation to supply regulation and net load following functions, the thermal plants would have a more stable operating regime, avoiding the negative consequences (i.e., increased emissions per kWh) of part-load operation and frequent cycling.

Source | Authors.

Energy storage costs vary significantly depending on the type of technology[35] (Figure 4.6). The data on the left in Figure 4.6 show the estimated cost range of equipment, while the costs on the right show total installed cost, including engineering, construction, and installation.

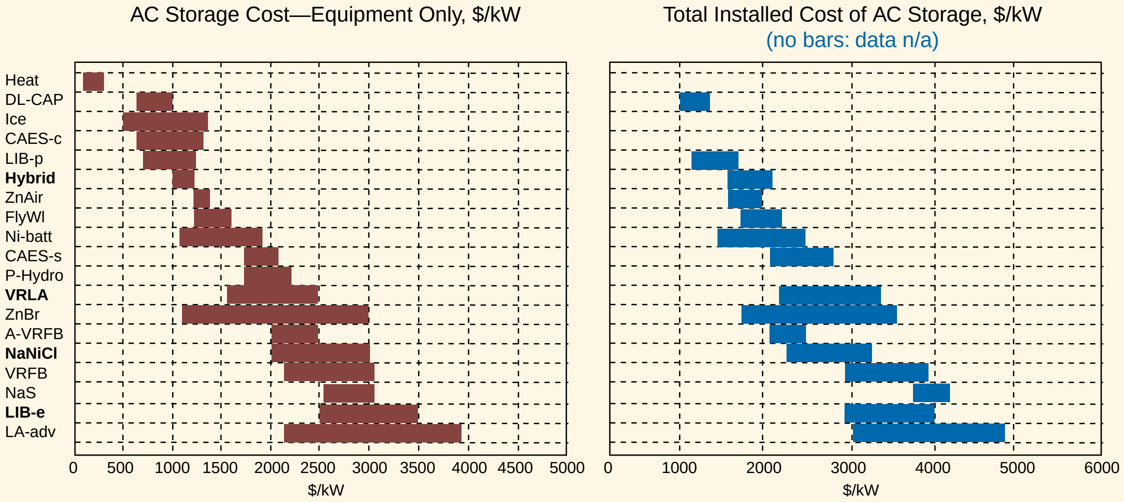
Site-specific storage options. Another limitation is linked to the fact that certain types of storage, such us pumped hydro or CAES, are site-specific and limited by resource, environmental, and social siting issues. In addition, in the case of pumped hydro, many large reservoirs behind major dams have dual functions (e.g., for recreational purposes or water storage). In these cases, the operation of the hydro power plants may be limited by constraints external to the power system. Moreover, the body of water on the low side has to be able to tolerate widely fluctuating inflow. A CAES typically requires areas with caverns to store the air, and many projects have been abandoned in the past due to siting problems. In the United States, for example, the 270-MW CAES in Des Moines, Iowa, and the 540-MW facility in Matagorda, Texas, were planned and studied for years, but were never built due to geological issues. Although no new CAES plants have been deployed since 1991, proponents of the technology are trying to overcome the geographic limitation with smaller modular CAES systems with above ground air enclosures or tanks. Considering the active R&D on new CAES technologies,[36] some analysts foresee a rapid market growth in the near future.

Uncertainty about profitability due to market and policy barriers. Storage technologies cannot recoup their capital costs in wholesale energy markets alone because it is difficult for storage to compete with generation technologies. The lack of markets for ancillary services in many countries/regions represents a barrier to the development of energy storage resources.

Even when ancillary service markets have been established, ancillary services prices may not be enough to consider storage a viable option. There is usually a gap between the market value and the grid value that is not properly rewarded, such as T&D investment deferrals. This, added to difficulties on determining market prices (lack of price signals), makes it challenging for independent operators to consider energy storage investments.

In addition, there are regulatory barriers for energy storage development that include unclear participation rules in the ancillary service markets and slow progress by regulators and planners in requiring storage to be part of the alternatives in planning and procurement for the power sector (SNL 2013).

FIGURE 4.6
Average Energy Storage Equipment Costs and Installed Costs, by Technology*



Thermal Storage (Hot)	Heat
Double Layer Capacitors	DL-CAP
Thermal Storage (Cold)	Ice
Compressed-Air ES, cavern	CAES-c
Lithium-ion—High Power	LIB-p
Hybrid LA & DL-CAP	Hybrid
Zinc-Air Battery	ZnAir
Flywheel	FlyWl
Ni batt. (NiCd, NiZn, NiMH)	Ni-batt
Compressed-Air ES, Small	CAES-s
Pumped Hydro	P-Hydro
Valve Regulated Lead Acid	VRLA
Zinc Bromide	ZnBr
Advanced Vanadium Redox Flow Battery	A-VRFB
Sodium Nickel Chloride	NaNiCl
Vanadium Redox Flow Battery	VRFB
Sodium Sulfur	NaS
Lithium Ion—High Energy	LIB-e
Advanced Lead Acid	LA-adv

**Costs are based on information gathered through interviews with energy storage manufacturers. Actual costs can be higher or lower depending on the specific storage technology selected.*

***Thermal Storage represents customer-sited thermal storage.*

Source | KEMA.

In the case of power systems with vertically integrated utilities, storage benefits are usually valued at the cost of the next best alternative for a particular application or service. This does not usually favor the development of storage systems because it is difficult for storage to compete with alternative generation resources using metrics such as levelized cost of energy. In order to properly value energy storage, it is necessary to use detailed simulations using software tools that can co-optimize multiple services provided by storage technologies, which can be done as part of detailed planned exercises in combination with VRE generation (NREL 2013).

Specific barriers to DES. In addition to the cost and siting issues, there are other barriers to the wide-scale implementation storage that affect especially small DES. These include:

- Lack of technology standardization and limited operating experience
- High cost of control and IT systems for interconnecting DES to effectively function as a larger unit
- Regulatory and market barriers for capturing multiple value streams; benefits from DES range from local to current mechanisms to remunerate DES are generally inadequate to compensate for all these benefits and provide incentives for investment

Prospects for Overcoming Storage Limitations

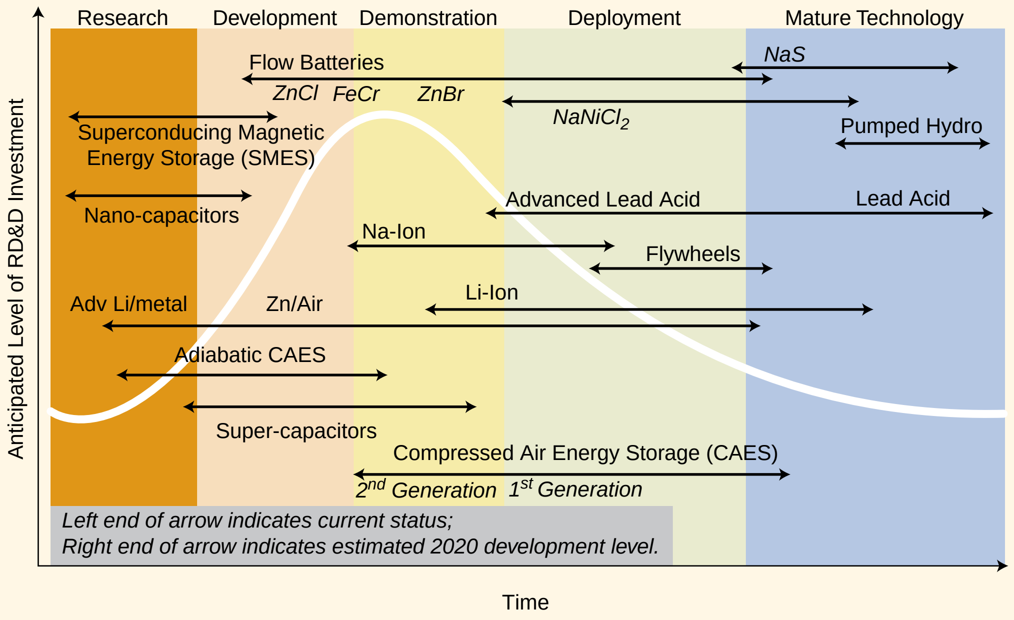
Researchers are continuing to improve older technologies and develop new ones. Several research initiatives are underway to improve materials and manufacturing processes. Progress is being made along all technology fronts affecting the scale, discharge duration, efficiency, response time, ramp rate, cost, and commercial maturity of most of the technologies. Figure 4.7 shows the current level of maturity of different devices and the level that is expected to be achieved by 2020 versus the level of anticipated investments for each one. Na-ion, Lithium-ion, lead acid, flow batteries, CAES, and super capacitors are expected to benefit from substantial R&D investments and become mature technologies in the next five years.

With regard to batteries, recent technological developments supported by favorable regulatory frameworks in Europe, the United States, and Asia have already contributed to reducing costs and space requirements, increasing the range of capacity, and extending warranties.[37] Some battery technologies are quickly becoming more competitive. Cost projections for lithium-ion batteries for power storage applications (i.e., fast response, limited capacity) forecast a reduction from $3,500/kWh in 2012 to $500/kWh by 2030. The costs of the same technology (lithium-ion) for higher capacity, slower response energy storage are expected to fall from $1,000/kWh in 2012 to around $200/kWh by 2030 (Pacific-Northwest-Laboratory 2012).

Flow batteries, which perform well for longer discharge applications than Lithium-ion, show a promising learning curve (Research 2011). The US Department of Energy (Office of Electricity Delivery and Energy Reliability's Energy Storage Program) is funding research to develop next-generation

FIGURE 4.7

Anticipated Research and Development Investment for Utility Scale Storage Technologies



Source | *Rastler, D. 2011. "Energy Storage Technology Status" presented at the EPRI Renewable Council Meeting.*

Vanadium Redox Flow Batteries aimed at reducing costs by improving energy and power densities, widening the operating window, and simplifying and optimizing designs.[38] The current total system cost of a 1-MW peak power to 4-MWh energy Vanadium redox battery is around $480/kWh, and it is estimated a reduction to $200 to 350/kWh in the near term (Pacific-Northwest-Laboratory 2012).

Flywheels are expected to find their position in the market for frequency regulation and other niche applications that require rapid discharge capabilities, short durations, and extremely frequent cycles (Research 2011).

Storage technologies can provide multiple benefits to the grid (balancing, regulation, contingency reserve, etc.). However, when evaluating the cost-effectiveness of a storage technology, the tendency is to consider utilization of the storage device for a single service/role. An assessment of the device's financial and economic viability is then based on revenue anticipated from that service alone. Industry participants are seeking to increase utilization modes and revenue streams generated by storage devices by offering multiple services from a single storage device to the grid. For example, an electrochemical storage devices could provide both grid support and variable renewable balancing services and be remunerated for both. The combination of applications that yields the maximum financial value would depend on each power system. Prioritization schemes must be selected amongst multiple applications at multiple points in time and additional testing and demonstrations of the storage device capabilities under different running models are needed to confirm the performance and benefits conceptualized for this approach for a particular power system.

ENDNOTES

[28] Storage capacity can be called upon in the event of a contingency such as the sudden, unexpected loss of a generator.

[29] Oshawa Power Hybrid PV Pilot Program in Ontario will involve approximately 30 residential rooftop solar PV systems that will be combined with energy storage and an energy management system by Spring 2015.

[30] For example, since 2012, the battery solar pilot program of SolarCity in California has managed to get around 500 customers to participate, even though only a limited number of those customers have battery systems connected to the grid due to the interconnection fees demanded by utilities (https://gigaom.com/2014/03/20/a-hurdle-for-tesla-and-solarcitys-grid-batteries-utilities/). To eliminate this barrier, the California Public Utilities Commission has recently clarified the existing policy to emphasize that storage meets the requirements to be considered an "addition or enhancement" to net-metering-eligible systems, and should be exempt from interconnection application fees, supplemental review fees, costs for distribution upgrades, and standby charges when interconnecting under the current net-metering tariffs (http://docs.cpuc.ca.gov/PublishedDocs/Efile/G000/M089/K641/89641289.PDF)

[31] Storage technologies can help to defer T&D investments, as explained above.

[32] In inverter-based power supplies, 60/50 Hertz direct current power is fed into an inverter (prior rectification, if necessary) where it can be switched on and off at very high frequencies, allowing for very fast response. Inverters convert direct current to alternate current.

[33] Harmonics are voltages or currents at frequencies that are a multiple of the fundamental frequency. For instance, in 50-Hz systems, the harmonic order is 100 Hz, 150 Hz, 200 Hz, etc.

[34] Wind turbines with induction generators have caused voltage problems at the feeder level in several countries. Modern wind turbines, however, can improve power quality since their converters can provide power smoothing, if properly set.

[35] It is customary to describe the costs of energy storage technologies in terms of $/kW over a number of hours. Some stakeholders prefer to view energy storage cost in terms of $/kWh. This number can be simply derived from the duration that is assigned to each of the technologies.

[36] http://www.navigantresearch.com/newsroom/compressed-air-energy-storage-to-experience-dramatic-growth-over-the-next-10-years.

[37] Some manufacturers, such as Samsung SDI, are offering a 20-year warranty on its battery cells (Bloomberg presentation at World Bank).

[38] http://energy.gov/sites/prod/files/VRB.pdf

5

PLANNING, POLICY, AND REGULATION CONSIDERATIONS

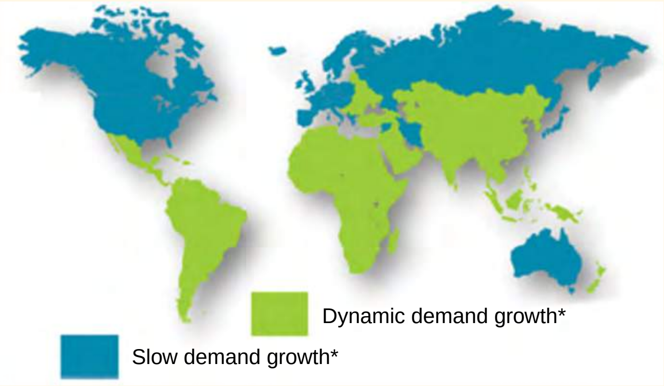
FINANCIAL VIABILITY OF EXISTING GAS-FIRED POWER PLANTS

Important lessons in terms of the impact of VRE on the commercial viability of existing natural gas generation can be learned from countries that have had experience in integrating high levels of VRE into power systems, with implications for broader energy sector policy and planning.

The impact of high shares of VRE on the rest of the power system depends fundamentally on demand growth. In countries/regions with slow demand growth or "static" power market, adding new VRE capacity has the effect of reducing the net load. When VRE plants are generating electricity, other conventional plants, mostly gas-fired, are forced to reduce output.[39] Countries like Australia (particularly in South Australia), Denmark, Germany, Ireland, Spain, and several states in the United States are successfully managing high levels of VRE (NREL 2012). In some of them, however, high shares of VRE has led to a considerable reduction in the utilization factor of the conventional power capacity as well as a reduction in efficiency, with consequences for financial viability as discussed below. In countries experiencing high demand growth (dynamic power markets), there is room to add both new VRE and new conventional generation capacity. While the lessons are derived from countries with overall low demand growth, the issues are also relevant for countries experiencing high demand growth with a goal of reaching high VRE penetration.

FIGURE 5.1

Global Distribution of Dynamic and Static Powers Markets



Source | *IEA*

BOX 5.1

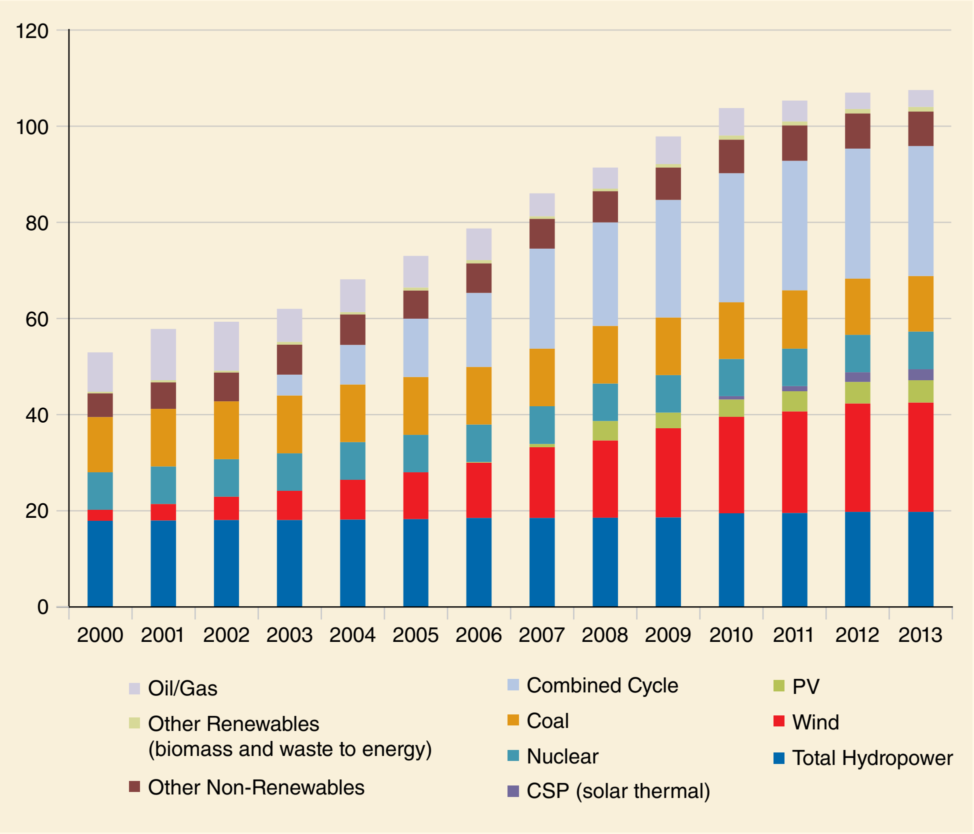
Use of CCGT for the Integration of VRE in Spain

Spain has more than doubled the generation capacity installed since 2000, from 53 GW in 2010 to 108 GW at the end of 2013.

This growth has been driven by the need for significant additional capacity (no new capacity had been installed between 1995 and 2000). Tight reserve margins and high demand growth projections encouraged operators to develop 67 new gas combined cycles between 2002 and 2011 (25.3 GW). Additionally, extremely favorable support schemes for variable renewable energy sources from 2004 to 2012 (Real Decreto 436/2004, Real Decreto 661/2007, and Real Decreto ley 6/2009), accelerated the development of wind and solar.

As a consequence, VRE and CCGT generation capacity have become the two largest sources of generation in terms of installed capacity. Two-thirds of old conventional oil/gas-fired units have been decommissioned (from 8.2 to 2.8 GW).

Evolution of Generation Mix in Spain



Source | Elaborated by Authors with data from Red Electrica of Spain and Iberdrola.

VRE integration in Spain has not been simple since adjustments to the balancing area were not possible due to the geographic dispersion, diversified ownership of the generation facilities, and the very limited interconnections of

(continued)

BOX 5.1 (CONTINUED)

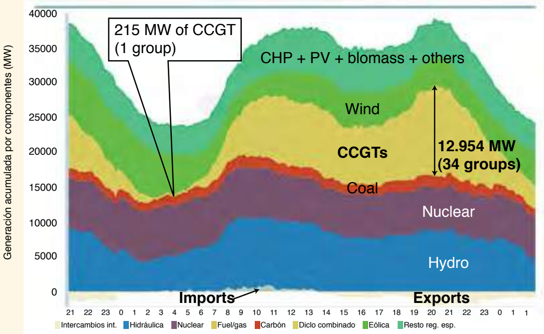
Spain with other countries. However, the flexibility of the system (provided mainly by the NG-based generators) combined with advanced forecasting and advanced unit commitment has allowed VRE plants to frequently serve 50 to 60 percent of the demand without posing reliability issues for the system.

Red Electrica de España (REE) established the first dedicated renewable energy power control center (CECRE), which is responsible for forecasting, controlling, and scheduling renewable energy generation. The use of advanced forecasting techniques has led to very accurate predictions, even for day-ahead forecasts. The regulatory framework has also contributed to the implementation of advanced forecasting. As a condition of benefiting from the generation VRE incentives, VRE plants with capacities higher that 10 MW must be connected to a centralized dispatching center or establish their own predictions and execute the operator's orders in real time. Moreover, VRE (wind, PV, and hydro) generators inscribed in the regulated tariff are requested to predict the amount of power to be produced one day in advance (one hour before the market closing time). Penalties for deviation from predictions are proportional to the deviations from real production, encouraging producers to achieve better predictions to increase revenues. Recently, solar forecasting has been introduced in system operations. This will help the system operator to improve the aggregated forecast, and minimize the amount of operational reserves that need to be committed for balancing and regulation.

Flexibility to manage the variability and forecast errors has been provided by moving CCGTs from primarily mid-merit operation to a much more flexible load following operating regime to successfully integrate these high levels of VRE generation (see figures below). This illustrates the role that NG-fired generation, in combination with state-of-the-art forecasting, can play in providing flexibility. However, the increased share of VRE has also created significant financial pressure on the new CCGT plants under the static power demand caused by the economic crisis in the country.

Feed-in-tariffs for new renewable energy installations have been suspended in Spain since January 2012 and retroactive feed-in-tariffs reductions were introduced in February 2013.

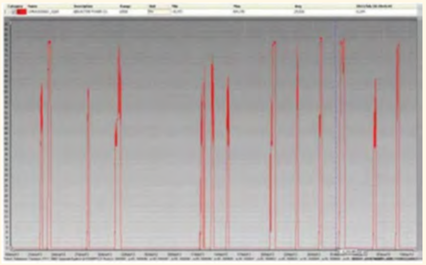
Breakdown of Generation in Spain (March 3, 2010)



Source | *Graph elaborated by Endesa with information from Red Electrica.*

The figure above illustrates an extreme situation on 3 March 2010 when only one CCGT unit was operating during off-peak hours, while up to 34 CCGT units were running during peak hours.

Operation of Combined Cycle Gas Turbines



Source | *UNESA for Eurelectric (Eurelectric 2014).*

Figure above shows the number of startups of a combined cycle in Spain over a six week period. When running, they are only operating for a few hours.

Source | *Ceña & Gimeno (2011), Endesa, (2012), Eurelectric (2011; 2014), and Red Electrica de España.*

Experience in Europe and the United States show that the financial viability of plants that are developed on a base-load or mid-merit load generation business models, are negatively impacted if subsequently the plant is pushed into a load-following mode of operation to balance VRE. This dynamic has led to losses for the utilities that own those assets as return on investments and even covering operational costs is uncertain. Some of the contributing factors are:

- In many countries, VRE plants have priority of dispatch, or their low marginal cost allows them to be dispatched first. Gas-fired technologies that were initially conceived to run as base-load or mid-load are forced to run at much lower capacity factors. Growing VRE shares in Europe have led to a decline in the number of operating hours of gas-fired generators, electricity sales, and revenues (Eurelectic 2014).
- The participation of VRE in power pool markets contributes to the reduction of wholesale electricity prices, since they have lower marginal costs, leading to very low or even negative electricity prices.
- Making use of the flexibility of gas-fired power plants (i.e., cycling and frequent ramp-up and turn-down) on a regular basis increases maintenance costs and reduces the operating life and efficiency. Gas generators can be modified to run in more flexible modes, but this requires re-engineering that may invalidate the equipment suppliers' guarantees (Eurelectic 2014). Recognizing the growing importance of flexible generation, gas turbine manufacturers are designing new models intended for flexible operation (see Figure 2.9).

The negative impact on existing gas-fired generation has potential implications for longer term adequacy and stability of the power grid as a consequence of the reduced investment in dispatchable, flexible plants. In some countries, the loss of revenues for gas-fired power plants has contributed to important utility share price falls,[40] and, ultimately, to the decommissioning of some plants, as well as lack of appetite for new investment. This has raised concerns about the capability of power systems to meet peak demand (adequacy) in the medium to long term (Euroelectric 2014). In addition, this has contributed to a phasing-out or elimination of VRE incentives in some countries.

Several solutions have been proposed, which would help remedy the current situation, and could be applied by authorities in countries at the beginning of a planned VRE scale up. The underlying concept is that certain services—e.g., firm capacity and flexibility—are essential in a system with high VRE penetration. The value of these services should be recognized and compensated, for example, through advances in market design and market management.

INCENTIVIZING FLEXIBILITY AND CAPACITY

Flexibility, achieved through a combination of approaches—interconnecting complimentary systems, demand response measures, flexible generation, and storage—is essential for integrating high levels of VRE. A sufficient level of capacity is also necessary to ensure that peak demand of a system will be met. Where market forces are effective in the power sector, flexible resources and capacity could be incentivized through capacity and flexibility markets. Operators of an electricity system then can procure an adequate mix of the amount of capacity necessary to ensure reliable delivery of electricity. For the most part, flexibility and capacity requirements should be technology agnostic in the absence of a strong reason to use a specific technology.

Options include:

- **The introduction of capacity markets** or **capacity regulated remuneration mechanisms** (flat rates or competitive auctions for a block of capacity) to provide an additional source of revenue beyond the scale of kWh to dispatchable, flexible technologies and ensure long-term adequacy in the system. A capacity market is a "forward market" aimed at driving capacity investments three to five years ahead of when power needs to be delivered. Capacity markets are open to generating resources—both conventional and renewables—and demand-side response. The grid operator holds an annual auction based on the power demand forecast for three years ahead. Generators bid, offering their capacity commitments at their total operating costs. The auction stops when the capacity requirement identified by the grid operator is covered. The remuneration is based on the "clearing price," which is the price of the most expensive capacity unit necessary to meet the identified capacity requirement. These types of markets have been recently introduced by some operators in some balancing areas.[41]
- **The establishment of forecasting and balancing obligations for VRE operators** (as presented in the case of Spain in Box 5.1).
- **The introduction of flexibility markets**, or regulated **remuneration mechanisms for flexibility suppliers**. Flexibility markets are a type of ancillary service market that provides remuneration to generators having the flexible capacity available for providing regulation, load following, or contingency reserves.[42]
- **Incentivizing energy storage.** National government policies and incentives can help overcome the barriers to energy storage. The portfolio of policies and regulations employed in a given country ultimately need to be adapted to address the challenges posed by its particular market structure and situation. Broad policy approaches can include the following:
  - Defining the regulatory asset classification of energy storage
  - Creating national standards for energy storage technologies and applications
  - Designating government-funded research, development, & deployment (RD&D) for innovations in energy storage materials and manufacturing to help lower the costs of storage components and national demonstration programs for energy storage technology and application validation
  - Establishing a coordinated program of demonstration projects among geographically diverse electric utilities can help validate storage applications, identify optimal configurations, and identify potential barriers (Box 5.2)

BOX 5.2

Emerging Storage Regulation and Incentive Programs

In Europe, there is specific energy storage regulation in at least seven countries and open discussions on the topic in most of the other countries. Some of the most relevant programs are in Germany, the United Kingdom, and France.

- In Germany, the Energy Turnaround initiative (Energiewende), has approved EUR 132 million to 49 R&D institutions and pilot plants focused on power-to-gas, CAES, and renewable energy integration. In addition, Energiewende exempts new built and refurbished storage from network usage fees and ensures that stored renewable energy will benefit from the same tariffs as renewable energy directly fed into the grid.
- In the United Kingdom, support schemes for Low Carbon Networks provide demonstration funds for innovative projects. In 2012, Low Carbon Networks Fund awarded GBP 45.5 million for energy storage. In May 2013, the Department of Energy and Climate Change (DECC) awarded the first GBP 2 million of a total of GBP 20 million to 12 demonstration projects and 4 research and feasibility studies. Additional GBP 30 million for R&D facilities for grid-scale storage were announced in Jan 2013.
- In France, tenders for wind and solar projects with energy storage for island states were awarded in 2012 and permitting expected in 2013. French Environmental and Energy Resource Agency (ADEME) awarded smart grid projects that included storage in 2012.

In the United States, the funds provided by the federal government for energy storage activities totaled almost $185 million and supported projects valued roughly at $772 million in total. Associated with these projects was approximately 537 MW of storage capacity, including storage for ancillary services (20 MW), distributed storage (7.5 MW), CAES (450 MW), and storage associated with renewable power (57 MW). There is also support at the state level, such as in New York and California. In California, after a long debate on the importance of storage for development of renewable energy, a recent mandate (October 17, 2013) from the California Public Utilities Commission (CPUC, 2013) has established an energy storage target of 1,325 MW by 2020. The storage capacity must be bought by California's largest utilities. The mandate specifies that the utilities cannot own more than 50 percent of the storage projects they propose. The action(s) utilities and third parties choose in order to comply with the mandate must be deemed to be cost effective by the CPUC. This regulatory decision is expected to help California integrate VRE, as per its own renewable portfolio standard to achieve 33 percent by 2020. Finally, there are additional programs promoted by systems operators such as PJM (Interconnection in the Mid-Atlantic region or CAISO (California Independent System Operator).

In Japan, the Ministry of Economy, Trade and Industry (METI) approved JPY 21 billion ($263 million) for subsidies for Lithium-ion batteries.

In India, the Ministry for New and Renewable Energy (MNRE) and the Power Grid Corporation of India (PGCIL) are evaluating the important role that both, small- and grid-scale energy storage projects could play in facilitating the integration of VRE. In July 2014, the MNRE issued a request for comments, observations, and feedback on a draft 'Expression of Interest for Energy Storage Demonstration Projects for Supporting Renewable Energy Generation.'

Source | Adapted from Bloomberg, ETH, and PV Tech Storage; European Commission 2013.

- Creating financial incentives. Options that have been tried include:
    - Allowing utilities to include investments in energy storage in their electricity rate-base
    - Giving utility tax credits to compensate local ratepayers for subsidies provided to DES (since DES can provide system-wide benefits to the grid)
    - Giving investment and production tax credits to incentivize energy storage demand and production
    - Offering accelerated depreciation tax incentives for energy storage investment
    - Providing grants or guaranteed loans to support energy storage manufacturing start-up and capacity development
- Developing national communication campaigns to increase stakeholder understanding of the applications and benefits of energy storage
- Including energy storage requirements within a national renewable portfolio standard or mandate and providing incentives for development of storage demonstration projects

IMPLICATIONS FOR NATURAL GAS DEMAND

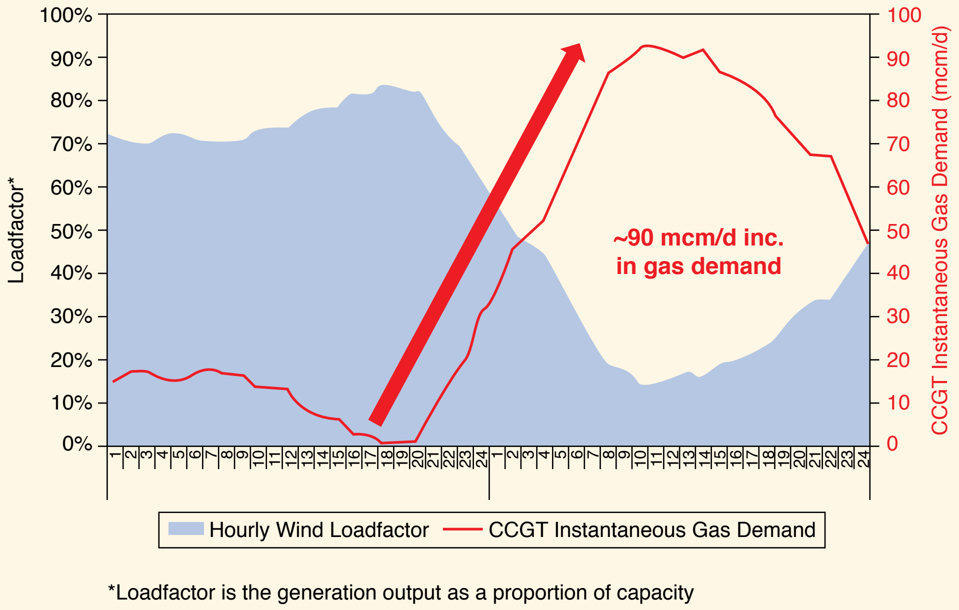
Variability in NG generation associated with increasing share of VRE can have implications for NG demand. The close link between scaling up VRE and gas-fired power generation has important implications for the interaction between the electricity and gas sectors. As VRE shares increase, to the extent that flexibility is provided by gas-fired generation, the power and gas sector become more interrelated. This implies the need for some additional flexibility in gas supply.

In a system with economic dispatching and a low level of VRE, gas-fired power generation assets are usually operated to provide base-load or mid-merit power, or, in the case of simple cycle gas turbines, peaking power; and gas consumption follows a predictable profile. However, in a system with high shares of VRE where NG units are following the variable net load, the demand for gas at the system and unit level becomes more variable and difficult to predict. Figure 5.2 shows the effect of a sudden wind decrease in the United Kingdom in 2000 on gas demand.

A recent report from Euroelectric (2014), based on the experiences of several European countries, emphasizes that gas system operators need to consider the impact of high levels of VRE in their operations. They need to work closely with power system operators to coordinate infrastructure investments and operating rules, with special consideration of the interactions between security of gas and electricity supply. Power system operators should receive sufficient information about their gas offtakes to manage their exposure to imbalance charges, especially if within-day purchase obligations apply. The flexibility of gas-fired generators may be limited by the flexibility of the gas supply. To maintain flexibility, gas infrastructure will need the capability to handle sudden up and down swings in gas demand. Gas procurement strategies and markets may need to be adapted to provide sufficient flexibility in gas supply.

FIGURE 5.2

Impact of Extreme Wind Events on Gas Demand



*Loadfactor is the generation output as a proportion of capacity

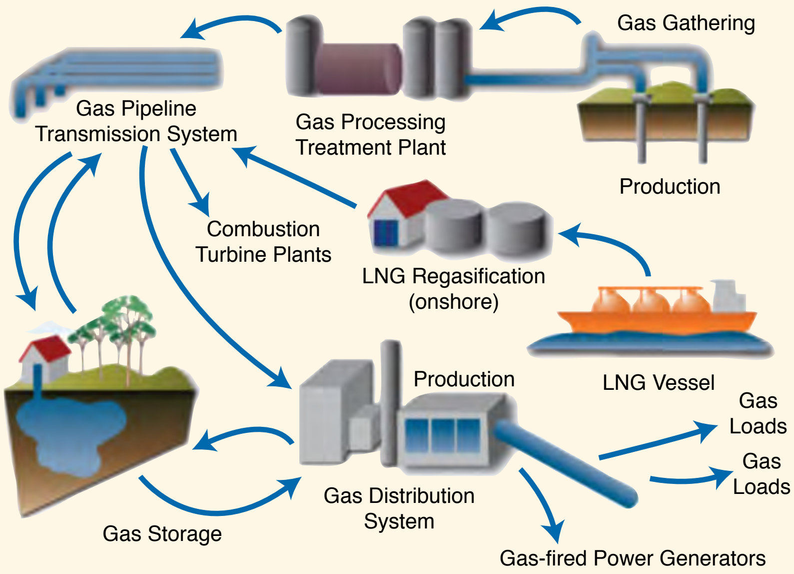
Source | *National Grid and Eurelectric 2014)*

In the United States, North American Electric Reliability Corporation (NERC) issued a Special Reliability Assessment in 2013[43] that analyzes the risks that natural gas reliance may pose to the electric sector's reliability. Some gas system operators are also commissioning their own studies to evaluate the impact of high shares of VRE on gas demand, and to determine whether the gas infrastructure available is adequate to meet the needs of the electricity sector (including the provision of flexible gas supply). For example, the Western Gas State Study[44] emphasizes that increased coordination between the gas and electric sectors will facilitate the interdependency between the two. This report shows that the variability of gas demand increases with the share of VRE, but the overall demand decreases. In this case, the variations can be accommodated by the planned gas infrastructure although operational challenges are identified.

Gas system operators can use several strategies to accommodate variability in gas demand, including NG storage, liquefied natural gas (LNG) trading, line-pack,[45] and varying production. The NG supply

FIGURE 5.3

Elements of Natural Gas Infrastructure



Source | Novi Energy.

chain requires complex gas infrastructure (Figure 5.3). If such infrastructure does not already exist, it would require substantial investments that may be too costly to develop for the sole purpose of supporting VRE integration. In those cases, other flexibility options, such as storage, could be more economic from the energy system point of view.

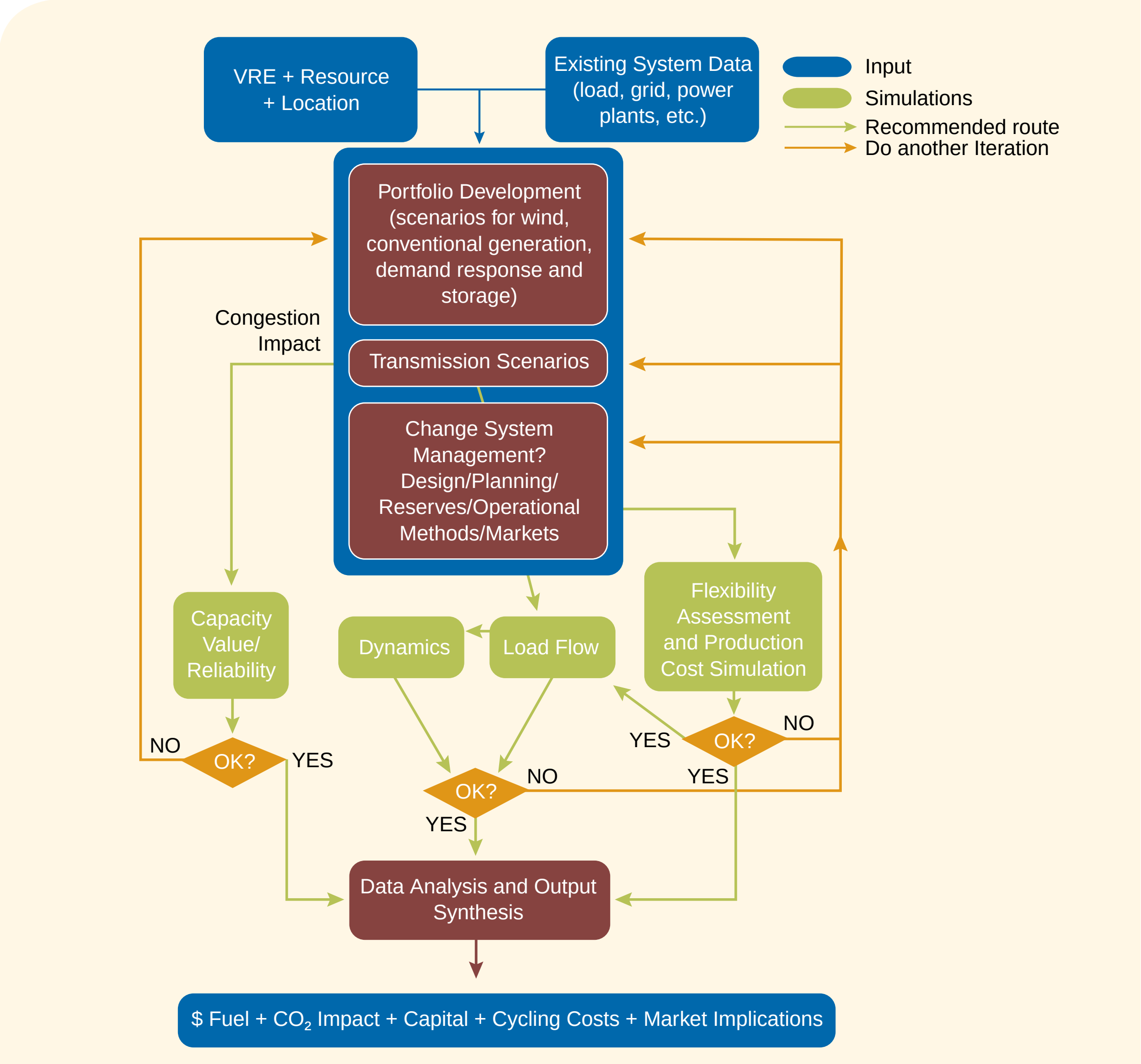
Providing flexible gas supply can be considerably more challenging, depending on the market structure and size. Large countries with significant gas infrastructure and competitive gas markets can more easily handle NG demand swings caused by VRE generation. Gas infrastructure planning should factor in the foreseeable flexibility of gas demand. Government's role can range from building and owning NG infrastructure and obtaining supply to providing incentives that attract private investment to develop the gas infrastructure to establish a credible sector structure and regulation.[46] Emerging small-scale LNG technologies could be a competitive option for some countries.[47]

TAKING CARE OF SHORT-TERM IMBALANCES IN LONG-TERM PLANNING

A comprehensive approach to planning can help to minimize VRE integration costs for the power system. System planning for the growing share of VRE should ensure development plans and specifications for both VRE (e.g., adequate targets and timeframes, geographical and technological

FIGURE 5.4

Recommended Loop for a VRE Grid Integration Study



Source | *Adapted from IEA Task 25 Report.*

diversification, interconnection and interoperability requirements, etc.) and conventional generation (e.g., increasing the amount of flexible generation in the overall systems, adapting existing power plants, maintaining efficiency, etc.) are aimed at achieving the least cost for the overall power system.

As shown in Figure 2.10, the performance of a power system is modeled at timescales ranging from years to fractions of a second, and across spatial regions from a local area to the whole system.

System planning generally focuses over longer timeframes. However, some of the potential issues associated with VRE variability and limited predictability occur at timescales that are typically assessed in short-term simulations (e.g., verification of the sufficiency of load following, regulation reserves, dynamic stability analysis). Some potential solutions, such as adding additional flexible generation capacity, are easily assessed in long-term planning models and others, such as implementing demand response measures, more readily assessed in short-term models. Hence, finding the optimal VRE integration approach may require an iterative modeling process between simulations of the impacts at the different timescales at which variability occurs (e.g., stability, balancing) and the least cost long-term planning models to achieve the specified level of reliability at the least overall system cost. Policy and regulatory framework and incentives informed by such planning should have the objective of minimizing total system costs, rather than VRE generation costs alone.

COMPETITIVENESS OF ENERGY STORAGE VS. OTHER FLEXIBILITY SOURCES

“Fast response” storage technologies can be a more effective technology choice than NG-fired flexible generation or fuel oil-based generation for certain applications related to VRE integration such as frequency regulation. Currently, high upfront costs limit “fast storage” perceived competitiveness. Depending on the case (i.e., gas and fuel oil prices and availability), however, storage may be able to contribute to VRE integration at a lower cost than available flexible generation technologies. For example, in the case of an island with limited interconnections and a power system based on a few fuel oil-based generation units, battery storage could be a competitive option. Uneconomic dispatching of fuel oil units may have a higher cost than the use of a battery for frequency regulation and load following. In addition, short-term storage systems (low capacity, fast response) are more effective than some other flexible options, as shown in studies for Aruba and Maui (Tsuchida 2014).

A recent US Department of Energy report (Pacific-Northwest-Laboratory 2012) compared the capability of different storage technologies with gas-fired generation and demand response (only electric vehicles considered) to meet balancing requirements. The objective of the study was to ascertain how to meet the future (2020) balancing requirements in several sub-regions of the United States in the most cost effective way. Balancing requirements span from intra-hour to inter-hour balancing and are driven by the load and wind forecast errors. The study focused on the intra-hour balancing that would be required by the Western Electricity Coordinating Council (WECC) to meet a 20 percent wind share target by 2020, concluding that the additional balancing requirements would range between 3 and 5 percent of the peak load in a given region. The study calculates the capacity required to meet the balancing requirements with different storage technologies, using CTs as the base-case of the comparison. The lifecycle cost (LCC) analysis shows that Na-S, flywheels, and pumped storage technologies have already lower LCOE than CTs when used for intra-hour balancing purposes and foresees that Li-ion and Redox flow batteries would become competitive by 2020.

COMBINED USE OF FLEXIBILITY MEASURES

The combination of flexible generation (gas or fuel oil-fueled) and energy storage plants (medium- and short-response duration/storage time) can help to improve the efficiency of the system. It can avoid base-load and mid-merit gas-based power plants being burdened with the need to respond to very short time variations, thereby reducing associated fuel costs and number of start-ups. Against these benefits is the cost of the storage both in terms of equipment cost and the energy lost during the charge/discharge cycle. Decreasing prices of advanced storage technologies will determine the future role of storage in VRE integration in combination with flexible generation.

ENDNOTES

[39] A point may be reached when there is not enough flexible capacity to scale back to accommodate the full VRE generation. In this case, excess production from the VRE plant would be transported to another system willing to absorb it (if available), store it (when possible), or curtail it (if there is no other option available).

[40] http://www.economist.com/news/briefing/21587782-europes-electricity-providers-face-existential-threat-how-lose-half-trillion-euros.

[41] More detailed information about PJM capacity markets is provided in Ott (2014) and PJM (2014).

[42] The way these markets work and the remuneration mechanisms are described in iF.P.(2013) and Ela, Kirby, Navid, and Smith (2012).

[43] http://www.nerc.com/pa/RAPA/ra/Reliability%20Assessments%20DL/NERC_PhaseII_FINAL.pdf.

[44] http://westernenergyboard.org/wp-content/uploads/2014/03/SPSC_Ph_1_Exec_Summ_West_Gas_Elect_Report_3-17-20141.pdf.

[45] Line-packing involves temporarily storing gas in the pipeline system by injecting more gas than is being withdrawn, allowing gas pressure to increase to the maximum operating pressure for the piping. Subsequently, to meet increase in demand, more gas is withdrawn from the pipeline compared to the amount of gas that is injected into the pipeline.

[46] Experiences in some countries show that the availability of large volumes of gas is not enough to create demand for gas in end-user markets. In markets where the government has not played a central role in creating a natural gas infrastructure, rapid gas development has not taken place (Baker Institute, 2005).

[47] http://next-decade.com/small-scale-lng/.

6

CONCLUSIONS AND RECOMMENDATIONS

As the share of VRE increases, the characteristics of VRE generation—variability, limited predictability, and site-specific nature of the resource—can affect the reliability, stability, and power quality of a power system. Addressing these issues implies a cost of integrating VRE into the power system that is incremental to the cost of power generation from a VRE power plant. It is therefore important that policy and planning focus on keeping the overall system cost of supply as low as possible (subject to performance objectives and targets) rather than looking to minimize the cost of generation from individual power plants.

A comprehensive approach to system planning that considers the full range of options to address integration issues can help to minimize VRE integration costs. Some analyses (IEA 2014) show that high shares (above 30 percent) of VRE could be achieved at modest additional overall electricity cost over time by explicitly planning for the best combination of VRE integration measures. Current modeling tools still have some limitations representing certain VRE characteristics, but they can still help identify future operational issues, simulate the mitigation effect of different solutions and operational strategies, and find the least cost option for the system through an iterative process.

A key option for VRE integration is to increase the level of system flexibility over time as the share of VRE increases in order to maintain reliability, stability, and power quality of the power grid system. Depending on the existing demand and energy mix, system flexibility can be increased through a combination of: interconnecting complementary balancing areas; adding flexible generation technologies that can adjust the level of power output quickly and frequently; and introducing demand-side flexibility, which can adjust demand through smart grid technologies and/or demand response management, and storage technologies. Policy-makers and regulators should recognize the value of flexibility in the system, and define remuneration mechanisms for flexible capacity. For the most part, flexibility requirements should be technology agnostic in the absence of a strong reason to use a specific technology. This report discusses two options for adding flexibility to a power supply system: natural gas-fired power generation and energy storage.

Most NG-fired power generation technologies have characteristics that make them suitable for providing generation flexibility to facilitate the integration of VRE, though with some limitations. Most NG-fired technologies have fast start-up times, ramp rates, and low turn-down ratios compared to other thermal generation options, allowing them to participate in balancing and regulation services as spinning and non-spinning reserves. However, NG generators do have limitations in the start-up times, ramp rates, and turn-down ratios so there is a limit to the amount and type of flexibility they can provide. In addition, part-load operation increases emissions and maintenance costs per unit generated, and reduces the operating life of the equipment. In regions with high shares of VRE, the financial viability of flexible NG-generation power plants has been negatively affected by the low utilization factor of the plants (as they become load following rather than base-load) and additional maintenance costs. Remuneration mechanisms for capacity and flexibility service are required to ensure long-term adequacy to meet peak load and enough flexibility to avoid instability issues.

Variability in NG generation associated with an increasing share of VRE can have implications for NG demand. The close link between a scale up of VRE and gas-fired power generation may imply the need for some additional flexibility in gas supply. Policy-makers, planners, and system operators in the electricity and gas sectors need to consider the impact of high levels of VRE. They must coordinate closely on planning, infrastructure investments, and operating rules to achieve security of gas and electricity supplies.

Storage options, in combination with or independent of flexible generation, have the potential to address most aspects of VRE integration associated with variability and limited predictability. Currently, deployment is limited by cost and limited track record in commercial operation. However, ongoing RD&D efforts are expected to lead to cost reductions and a more robust track record in the medium term. Medium- and long-term planning for the scale up of VRE should take into account the projected improvements in planning scenarios.

ANNEX 1 | ADVANCED VRE OUTPUT FORECASTING

Enhanced measurement and forecasting of VRE output is needed to ensure power system reliability, in both operations and long-term planning horizons. Significant progress has been made in this field over the past decade. Advanced energy markets integrate VRE forecasts to maximize the benefits, and forecasting techniques are being incorporated into real-time dispatching and scheduling in many countries.

VRE forecasting can be classified in ultra short, short, and medium/long term, with short-term (48 to 72 hours in advance) forecasts being the most used by operators (IEC).

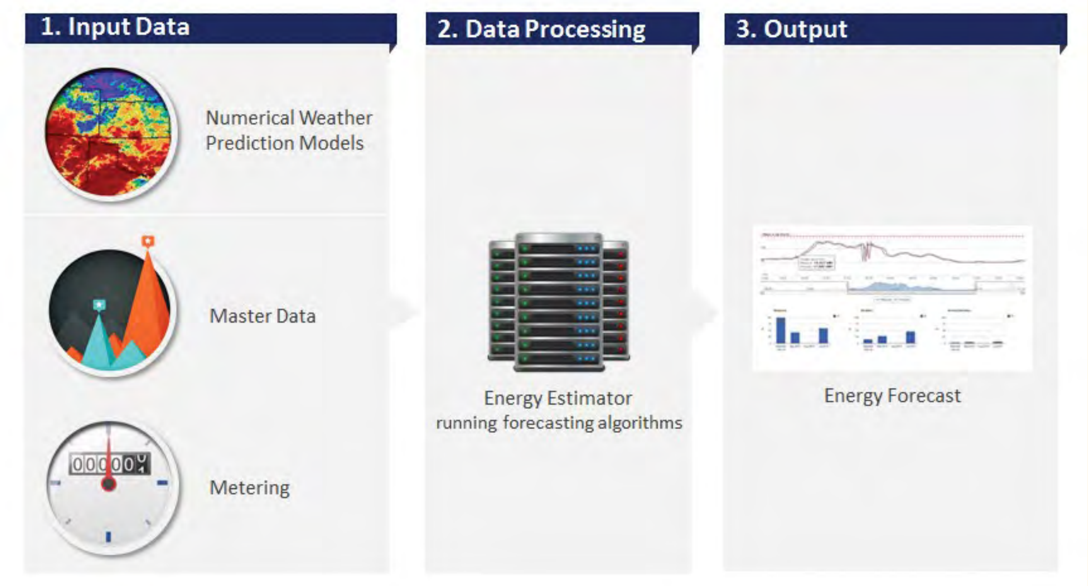
Advanced forecasting systems involve several components (GNARUM):

- **Master data.** Main power plant characteristics that include location, power plant characteristics, installed capacity, specific technical configuration, digital terrain model, and other special characteristics.
- **Numerical Weather Prediction Models (NWP).** Mathematical models that solve a complex set of equations describing the physical laws that determine the state of the atmosphere and oceans that are used to predict the weather based on measured initial conditions. NWP models can be global (with time resolution of hours), regional (with spatial resolution around 1 to 2 km and time resolution of minutes), or micro-scale models (with spatial resolution of meters and time resolution of seconds). NWP is usually the main source of error in the forecast of power generation.

  HiRLAM (High Resolution Limited Area Model) and GFS (Global_Forecast_System) from NOAA are examples of NWP models.
- **Metering systems.** Metering systems can be offline (producing periodic updates), online (daily updates), or real time. The main parameters of interest are weather variables—wind, pressure, radiation, temperature, and humidity—and output power of VRE.
- **Output energy estimation models.** Many approaches have been developed in the literature. Different target objectives lead to different strategies, depending on the data availability. Different approaches include:
    - **Theoretical (physical) approaches.** Output energy is obtained as an analytical function of a set of input parameters. Solar power plant physical models use equations to compute in-plane module radiation, direct current power, and output energy. For wind power plants, physical models use the turbine power curve to estimate output power and the wind power plant energy is the sum of every turbine minus wake effects, theoretically modelled. As an advantage, these models do not require historical data and are easy to implement, but are very sensitive to parameter misconfiguration.

FIGURE A1.1

Schematic View of the Component of an Advance Forecasting System



Source | Gnarum. For more information, see World Bank-ESMAP RE training (available at: https://www.esmap.org/sites/esmap.org/files/ESMAP_IFC_RE_Training_Gnarum_Castano_I.pdf).

- **Statistical approaches**. Output energy is obtained through statistical analysis of historical data. A power plant power curve is statistically modeled using learning algorithms (artificial neural networks (ANNs), regression methods or curve fitting), regression methods or curve fitting, and historical data to "train" the statistical models. These approaches produce a more accurate output, and adapt to the changes in the power plants, but require high quality historical data and high performance computational resources.
- **Combined approaches.** Output energy is obtained through a combination of theoretical calculations and statistical analysis.

Several physical and statistical programs are commercially available in the market and new models and findings are emerging rapidly (IEC and IEA 2013). IEC (2012, Section 3.4) provides additional information on commercial estimators available and how several countries have incorporated forecasting to power system operations. Dialogue between system operators and the research community will help ensure that appropriate accuracy metrics are targeted and become the focus of forecast improvement efforts.

ANNEX 2 | RELEVANT GAS-FIRED POWER GENERATION TECHNOLOGIES OF RELEVANCE FOR VRE INTEGRATION

TABLE A2.1

Relevant Gas-fueled Power Generation Technologies for VRE Integration

NG-GENERATION TECHNOLOGY	OPERATIONAL CHARACTERISTICS	AVAILABILITY OF VENDORS	OVERNIGHT CAPITAL COSTS ($/kW)	MAINTENANCE COSTS FIXED ($/kW-yr) VARIABLE (c$/kWh)	SITING CONSIDERATIONS
Microtubines and Miniturbines (MT)	Capacity Range Microturbines: 15–200kW Miniturbines: 200kW–1MW Peak Efficiency: 25–35% (new efficient designs up to 50%) Cold start: 2–10 mins Hot start: 2–6 mins Ramp-up Rate: 135kW/min Turndown Ratio: 10% Lifetime: 5–20 years (varies with size) Noise: Moderate (enclosure provided with unit)	Limited **Microturbines:** AlliedSignal, Capstone, Elliott MagneTek, GRI/Northern, Research, Teledyne/Ryan, Turbec, Flex Energy **Miniturbines:** AlliedSignal, Allison, Dresser-Rand, European Gas Turbines, General Electric, Greenwich Turbine, Kawasaki, Solar Turbines, Turbomeca, Flex Energy	1,500–3,000	Fixed: 6–10 Variable: 1.5–4	Ambient temperature and pressure have a noticeable effect on power output and efficiency. At elevated inlet air temperatures, both the power and efficiency decrease. Power and efficiency increase when the inlet air temperature is reduced. High altitude implies lower ambient pressure that reduces efficiency.
Open Cycle Gas Turbines (OCGT)	Capacity Range: 1–500MW* Peak Efficiency: 22–40% Cold Start: 15–20 mins Hot Start: 10–15 mins Ramp-up Rate: 8–20% capacity/min Turndown Ratio: 50% Lifetime: 25–50 years Noise: Moderate to High	Wide range GE, Rolls Royce, Kawasaki, Solar Turbines, Alstom, Mitsubishi Hitachi Power Systems, Siemens, etc.	500–950	Fixed: 7–15 Variable: 0.8–1.5	Ambient temperature and altitude have same effects as per MTs. Moving parts produce noise and vibration. Utility scale plants must be installed away from population centers. Small scale plants can be installed closer to cities with noise abatement systems.

NG-GENERATION TECHNOLOGY	OPERATIONAL CHARACTERISTICS	AVAILABILITY OF VENDORS	OVERNIGHT CAPITAL COSTS ($/kW)	MAINTENANCE COSTS FIXED ($/kW-yr) VARIABLE (c$/kWh)	SITING CONSIDERATIONS
Conventional Combined Cycle Plants (CCGT)	Capacity Range: 100–500MW* Peak Efficiency: 38–44% Cold Start-up: 180–200 mins Hot Start: 60–100 mins Ramp-up Rate: 4% capacity/min Turndown Ratio: 50% Lifetime: 30–40 years Noise: Moderate to High	Moderate GE, Alstom, Mitsubishi Hitachi Power Systems, etc.	850–1,000	Fixed: 13–15 Variable: 0.3–0.7	High land use (tens of acres). Operation associated with a level of lighting, ambient noise, cooling tower produces a visible moisture plume. Installed close to NG transmission pipelines and away from population centers.
FAST combined cycle power plants (FAST-CCGT)	Capacity Range: 100–500MW* Peak Efficiency: 60% Cold Start: 60 mins Hot Start: 35–40 mins Ramp-up Rate: 8% capacity/min Turndown Ratio: 40% Lifetime: 30–40 years Noise: Moderate to High	Limited GE, Siemens	950–1,700	Fixed: 15–17 Variable: 0.7–1	
Reciprocating Engines (Internal Combustion Engines, ICE)	Capacity Range: 15kW–20MW* Peak Efficiency: 28–55% Cold Start: 10–12 mins Hot Start: 10–15 secs Ramp-up Rate: 100% capacity/min Turndown Ratio: 30–50% Lifetime: 10–20 years Noise: Moderate to High	Wide range Wärtsilä, Caterpillar, Inc., GE, Cummins. Inc., etc.	900–1,300	Fixed: 2–17 Variable: 0.7–1.5	Moving parts produce noise and vibration. An increase in either altitude or ambient temperature can degrade the electrical output of the system.
Fuel Cells for power sector (stationary)	Capacity Range: 200kW–5MW* Peak Efficiency: 10–60% Warm-up Rate: 40–60 secs Turndown Ratio: 50% Lifetime: 15–20 years Noise: Low	Very Limited** UTC Power, Fuel Cell energy, Ballard Power, Bloom Energy	3,000–7,500	Fixed: 0 Variable: 2–5	Small footprint. Silent operation (may be installed closer to population centers) • High Efficiency/Low CO_2 • Distributed Installation • Modular/High Reliability Low/Zero Emissions

**Capacity of individual machine indicated in the table.*
***Some manufacturers limit their market to United States only.*

Source | Authors compiled information obtained from NOVI Energy (2012), ECOFYS, Papaefthymiou, Grave, & Dragoon (2014), WADE, and other sources, though cost data may not be totally consistent across all sources consulted.

TABLE A3.1a

Main Characteristics and Applications of Storage Technologies Relevant for VRE Integration

TECHNOLOGY OPTION	MATURITY	ENERGY RATING (MWh)	POWER CAPACITY (MW)	DURATION (HOURS)	% EFFICIENCY (TOTAL CYCLES)	INSTALLED COST ($/kW)	ENERGY INSTALLED COST ($/kWh)	ADVANTAGES	DISADVANTAGES
Technologies for Bulk Energy Storage to Offset Large Quantities of VRE Generation									
Pumped Hydro	Mature	1,500–15,000	100–2,500	8–16	80–82 (>13,000)	500–2,000	60–350	High capacity, low cost, long lifespan	Site specific
CAES (underground)	Commercial	1,080–3,600	100–2,000	8–25	(>13,000)	500–1,800	50–400	High capacity, low cost	Special site requirements, Need gas as fuel
Sodium Sulfur (NAS)	Commercial	300–720	50–100	6–7.4	75 (4,500)	3,000–3,200	450–510	High power and energy densities	Production cost/ safety concerns
Advanced Lead-Acid	Commercial/Demo	200–400	20–100	4–5	85–90 (2,200–4,500)	1,700–4,900	425–980	Low capital cost	Limited Cycle Life when deeply discharged
Flow Batteries (Vanadium Redox)	Demo/R&D	250	50	5	60–75 (>10000)	1,440–3,700	600–800	High capacity	Low energy density
Energy Storage for ISO (Independent System Operator) Fast Frequency Regulation and VRE Integration									
Flywheel	Commercial/Demo	5	20	0.25	85–87 (>10,000)	1,950–2,200	7,800–8,800	High power	Low energy density
Li-ion	Demo	0.25–25	1–100	0.25–1	87–92 (>10,000)	800–6,000	1,000–2,500	High power and energy densities, High efficiency	High production cost, Require special charging circuit
Advanced Lead-Acid	Commercial/Demo	0.25–50	1–100	0.25–1	75–90 (>10,000)	2,500–5,000	500–2,500	Low capital cost	Limited life cycle if deeply discharged

TECHNOLOGY OPTION	MATURITY	ENERGY RATING (MWh)	POWER CAPACITY (MW)	DURATION (HOURS)	% EFFICIENCY (TOTAL CYCLES)	INSTALLED COST ($/kW)	ENERGY INSTALLED COST ($/kWh)	ADVANTAGES	DISADVANTAGES
Energy Storage for Utility T&D Grid Support Applications									
CAES (above ground)	Demo	250	50	5	(>10,000)	1,950–2,150	390–430	High capacity, lowest cost	Special site requirements, need gas as fuel
Advanced Lead-Acid	Demo	3.2–48	1–12	3.2–4	75–90 (4,500)	2,000–4,600	625–1,150	Low capital cost	Limited Cycle Life when deeply discharged
NaS	Commercial	7.2	1	7.2	75 (4,500)	3,200–4,000	445–555	High power and energy densities, high efficiency	Production cost/ safety concerns
Flow Batteries (Vanadium Redox)	Demo/R&D	4–50	1–10	4–5	60–75 (>10,000)	1,200–3,310	300–1,350	High capacity	Low energy density
Zn/air	R&D	5.4	1	5.4	75 (4,500)	1,750–3,000	325–350	Very high energy density	Electric charging is difficult
Li-ion	Demo	4–24	1–10	2–4	90–94 (4,500)	1,800–4,100	900–1,700	High power and energy densities, High efficiency	High production cost, special charging circuit

Source | *Adapted from KEMA, EPRI, ECOFYS, ETH and other sources.*

TABLE A3.1b

Main Characteristics and Applications of Storage Technologies Relevant for VRE Integration

TECHNOLOGY OPTION	MATURITY	ENERGY RATING (kWh)	POWER CAPACITY (kW)	DURATION (HOURS)	% EFFICIENCY (TOTAL CYCLES)	INSTALLED COST ($/kW)	ENERGY INSTALLED COST ($/kWh)	ADVANTAGES	DISADVANTAGES
Energy storage for Distributed Applications									
Advanced Lead-Acid	Demo/ commercial	100–250	25–50	2–5	85–90 (4,500)	1,600–3,725	400–950	Low capital cost	Limited Life when deeply discharged
Zinc/Br Flow	Demo	100	50	2	60 (>10,000)	1,450–3,900	725–1,950	High Capacity, Independent ratings	Low energy density
Li-ion	Demo	25–50	25–50	1–4	80–93 (5,000)	2,800–5,600	500–2,500	High power and energy densities, High efficiency	High production cost, special charging circuit
Energy Storage for Residential Energy Management Applications									
Advanced Lead-Acid	Demo/ commercial	10–20	5	2–4	85–90 (1,500–5,000)	2,200–4,500	1,400–3,000	Low capital cost	Limited life cycle if deeply discharged
Zinc/Br Flow	Demo	9–30	3–15	2–4	60–64 (>5,000)	4,000–10,000	785–4,500	High Capacity, Independent ratings	Low energy density
Li-ion	Commercial	7–40	1–10	1–7	75–92 (5,000)	6,500–11,000	800–4,500	High power and energy densities, High efficiency	High production cost, special charging circuit

Source | *Adapted from KEMA, EPRI, ECOFYS, ETH and other sources.*

TABLE A3.2
Mechanical Storage Technologies

Illustration of a Pumped Hydropower Storage System

Bulk Energy Storage and Balancing Applications

Source | *US Department of Energy, GlobalEnergy Storage Database.*

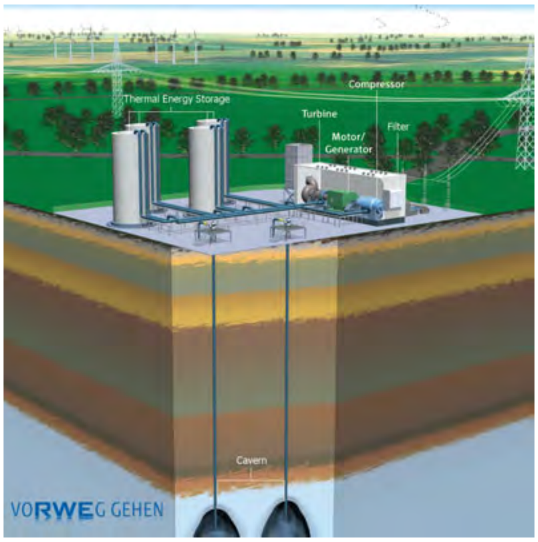
Pumped hydro storage uses two water reservoirs, separated vertically. The hydroelectric power plant acts both as a generator and a pumping facility. During off-peak hours, water is pumped from the lower reservoir to the upper reservoir. (See Box 4.1 describing the Ingula scheme.) During peak load periods, the water flow is reversed to generate electricity. In addition, some high dam hydro plants also have storage capability and can be dispatched as a pumped hydro system. The open sea can also be used as the lower reservoir.

Key features:
- Fully commercialized technology.
- Long economic life span (typically more than 50 years).
- High efficiencies (70–80%).
- Storage time between 4–10 hours.
- Low O&M, and lack of cycling degradation.
- Nearly immediate start-up, much faster than fossil-fueled thermal generation.
- Very specific siting requirements and investment costs tend to be high.
- Pumped storage can provide valuable scheduling and balancing services from intra-hour through multiple-day time periods

Pumped hydro storage is the most used and mature large-scale energy storage technology, with 129 GW of installed capacity worldwide.

Source | *ECOFYS 2013; Eurelectric 2011; KEMA.*

Illustration of a CAES Facility



Bulk Energy Storage and Balancing Applications

Source | *RWE Group Business Service GmbH*

Compressed air energy storage (CAES) stores energy by running electric motors to compress air into enclosed volumes (underground caverns or in above-ground storage tanks). The electrical energy is recovered when the stored compressed air is fed into a turbine. There are three different options of CAES available, depending on the expansion process in the turbine (diabatic, adiabatic and isothermal).

Key features:
- Subsystems are mature (commercialized technology).
- Conventional CAES requires fuel (natural gas).
- Efficiency of CAES units ranges from 40 to 75 percent.
- Units require 5 to 15 minutes to start up, and then can ramp up at a rate of 10 percent every 3 seconds in discharging mode and 20 percent per minute in charging mode.
- Important geology and siting-related restrictions for traditional CAES systems.
- Suitable for balancing large amounts of VRE generation, but they are not usually considered in providing regulation services.

There are two utility-scale CAES systems in existence: a 60-MW compressor, 321-MW generator built in Germany in 1978; and the 50-MW compressor, 110-MW generator Alabama Electric Cooperative McIntosh plant built in 1991. In addition, Pacific Gas and Electric is working on a demonstration 300-MW CAES plant with 10-hour storage capability.

Source | *KEMA & ECOFYS 2013.*

(continued)

TABLE A3.2
Mechanical Storage Technologies (Continued)

Beacon Power Flywheel Plant (Stephentown, NY)

Frequency Regulation Application

Source | *US Department of Energy, GlobalEnergy Storage Database.*

Flywheels store electrical energy by speeding up inertial masses that rest on very low friction bearings. Energy is transferred in and out using a motor generator that spins a shaft connected to the rotor. Rotor speed ranges from 1,800 to 3,600 rpm and the total weight can be around 3,000 to 6,000 kg.

Key features:
- Fully commercialized technology.
- Flexible siting
- Flywheel modules store 0.5 to 1 kWh of energy.
- Efficiencies range from 70 to 80 percent.
- Capacity ranges from 100 kW to 20 MW and discharge times from 5 seconds to 15 minutes.
- As frequent cycling and continuous operation wear down mechanical components, life expectancy of flywheels is a concern (expected life cycle of 100,000 charge-discharge cycles). Recent flywheel information from the company ABB shows a bearing serving life of eight years.
- Flywheels are generally considered short-discharge duration devices with instantaneous response time, making them an appropriate choice for frequency regulation and power quality applications.

Source | *ECOFYS 2013; KEMA, Red Electrica and SNL.*

TABLE A3.3
Electrochemical Storage Technologies

Illustration of an Advanced Lead-Acid Battery Installation

Source | *US Department of Energy, Global Energy Storage Database.*

Solid State Conventional batteries are cells that contain a **positive terminal,** or cathode, and a **negative terminal,** or anode, and electrolytes that allow ions to move between the terminals. During the charging cycle, the electrolyte is ionized; during discharge, an oxidation-reduction reaction recovers the energy. There is a wide range of battery types named for the electrolyte employed. Common ones include **lead-acid, nickel-cadmium (NiCd), and lithium-ion**.

Ni-Cd batteries have been used in energy-storage applications such as Golden Valley Electric Association BESS (27 MW for 15 minutes and commissioned in 2003) and for stabilizing wind power, such as the 3 MW system commissioned in the island of Bonaire (Caribbean Netherlands) in 2010.

Source | *ECOFYS 2013; KEMA and ESA.*

TABLE A3.3

Electrochemical Storage Technologies (Continued)

Illustration of a Sodium-Sulfur Battery Installation

VRE time shift, voltage support, ramping, and frequency regulation applications

Source | *US Department of Energy, Global Energy Storage Database.*

High energy/temperature batteries are based on reactions that occur at elevated temperatures (300 to 350°C). Common chemistries are **sodium sulphur (NaS)**, the most common, and **sodium nickel chloride**. Sodium Sulfur (NaS) technology was developed by Ford Motor Company in the 1960's and subsequently sold to the Japanese company NGK, that now manufactures the **"battery"** systems for stationary applications. The **"round trip efficiency"** is in the 90 percent range.

More than 270 MW of NaS batteries have been installed at over 190 sites in Japan. The largest NaS installation is a 34-MW, 245-MWh unit for wind stabilization in Northern Japan.

U.S. utilities have deployed 9 MW for peak shaving, backup power, firming wind capacity, and other applications. Projections indicate an additional capacity of 9 MW is under development.

Source | *ECOFYS 2013; KEMA and ESA.*

Illustration of a Vanadium Redox Battery Installation Coupled with PV

Application to support electric vehicle charging with PV solar power

Source | *Cellstrom GmbH.*

Flow batteries store the electrolyte material in external tanks. During charging and discharge cycles, the electrolyte is pumped into the cell stack. There are two types: **hybrid and redox**. Flow batteries are suited for energy applications, such as peaking generators and regulation reserves. Zinc/Bromine batteries are less mature than Vanadium Redox systems. Estimated lifetime of flow batteries is around 20 years. Estimated efficiencies are around 65–75 percent.

Source | *ECOFYS 2013; KEMA and ESA.*

TABLE A3.4

Chemical Storage Technologies

Power to Gas Facility Supplied by ETOGAS for Audi

Energy Shift Applications

Source | *ETOGAS*

Chemical energy storage uses excess electric energy to create hydrogen or hydrocarbons, which can be used as fuels (e.g., synthetic methane, hydrogen). When synthetic natural gas (SNG) is subsequently burned in conventional combustion engines, heating boilers or power plants, only the amount of CO_2 gets emitted, which has been added during production process (CO_2-neutral process). These projects are still in the demonstration stage, with Germany leading the research.

Audi opened a power to gas 6-MW facility in June 2013, supplied by ETOGAS, which produces enough SNG to operate 1.500 vehicles. The power is received out of the public power grid in periods of power surplus and the SNG is fed into the public gas grid. Customers that ordered the e-gas option for their new vehicles (for a flat monthly fee) can fuel at more than 900 natural gas stations throughout Germany. Audi ensures that the 6-MW-power-to-gas plant feeds in at least the amount consumed by the e-gas customers. The conversion efficiency of the 6-MW plant is higher than 50 percent.

TABLE A3.5

Thermal Storage Technologies

Illustration of a Chilled Thermal Storage Installation

Energy time shift, power quality, and reliability

Source | *US Department of Energy, GlobalEnergy Storage Database.*

Large-scale chilled thermal storage and small-scale cold thermal storage.

Thermal energy storage refers to storage technologies where instead of storing electric energy, as in batteries, or potential energy, as in pumped hydro, energy is stored as thermal energy.

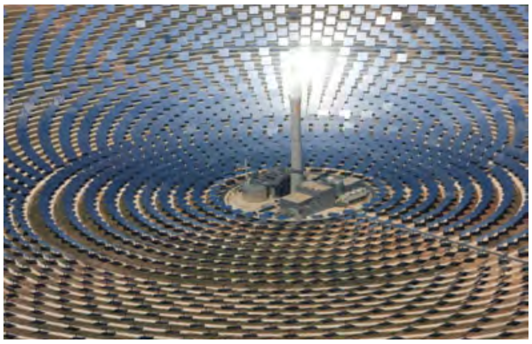
Thermal energy can be stored as:
- Sensible heat, as in hot water tanks or ice
- Latent heat, where the storage medium stores and releases energy by changing phase, for instance from solid to liquid
- Thermochemical heat, where thermal energy is absorbed or released via a chemical reaction

As there are energy losses involved with any energy conversion from electric to thermal or any other kind of energy, thermal energy technologies are most effective when used in situations where the end usage is thermal energy, as in heating or air conditioning, or when the energy supply is a thermal source.

Source | *KEMA.*

TABLE A3.5
Thermal Storage Technologies (Continued)

Molten Salt Tanks in Gemasolar Power Plant



Source | *Torresol Energy–SENER*

Thermal Energy Storage Technologies for Concentrated Solar Thermal Power (CSP): The leading technology for thermal energy storage at CSP plants involves a two-tank system storing a heat transfer fluid (HTF), typically molten salt. Many other technologies—solid media (concrete) and specially designed phase-change materials—are being developed, improving heat transfer characteristics, controllability, safety, economics, and other aspects.

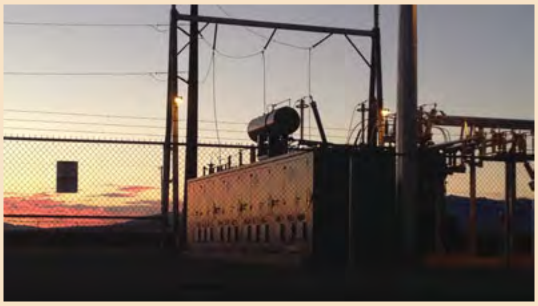
Gemasolar, owned by Torresol Energy, is a 19.9-MW solar tower that has been producing energy since October 2011 and is able to produce 24/7 energy thanks to solar thermal storage.

Other relevant examples include Abengoa's Solana 280-MW solar power station in Arizona with 6 hours of thermal energy storage and SolarReserve's 110-MW Crescent Dunes power tower solar thermal plant in Nevada, scheduled for completion in 2014, will have 10 hours of storage.

Source | *ECOFYS 2013; KEMA; Torresol Energy–SENER.*

TABLE A3.6
Electromagnetic Storage Technologies

Metal Enclosed Capacitor Banks



Injection of Reactive Power in Solar Power Plant to Meet Point of Interconnection Requirements

Source | *NEPSI.*

Capacitors help store power over short time horizons via electrochemical means or electrolytes. They typically have very fast response times, very low energy densities, and high cycle lives. Ultra- or super-capacitors are capacitors with energy densities hundreds of times greater than conventional capacitors. Their timeline for market penetration are very similar to flywheels (European Comission, 2013). For Solar Power Plant applications where solar heat gain from direct sunlight is an issue, enclosing the capacitors in a ventilated metal enclosure is a solution to ensure higher reliability and longer equipment life.

Source | *ECOFYS 2013; KEMA.*

TABLE A3.6

Electromagnetic Storage Technologies (Continued)

Illustration of a SMES Installation

Uninterruptible Power Supply Application

Source | Bruker EST.

Superconducting Magnetic Energy Storage (SMES) store energy in the magnetic field created by the flow of direct current in a superconducting coil. The primary cost components of SMES are the superconductor and the associated cooling system, which also poses installation challenges. Up to now, most of the research conceptualized short-duration units for power application. However, some suppliers (such as ABB) are examining a device that could provide significantly higher energy density at lower cost than traditional lead-acid batteries.

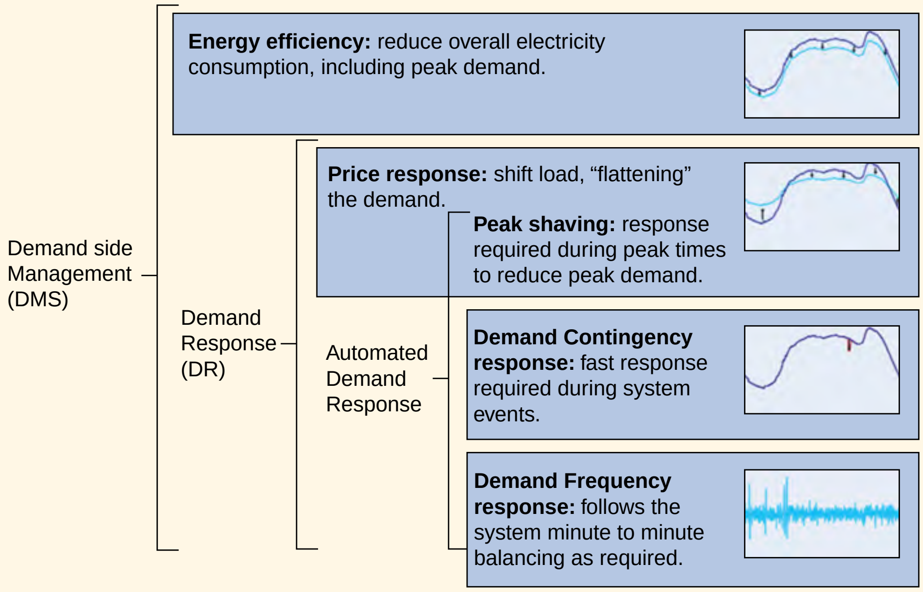
Source | ECOFYS 2013; KEMA.

ANNEX 4 | DEMAND RESPONSE

Demand-side management (DSM), which includes demand response (DR) and investments in energy efficiency, is seen as an effective resource for limiting required investments in transmission and operating reserves (Kirby 2006). The Figure A4.1 shows the different types of DMS mechanisms that are currently available and how they affect the demand. All DSM options, including energy efficiency programs, can be potentially useful in facilitating VRE integration.

In the case of DR mechanisms, the demand is modified in response to the request of the system operator in order to accomplish a specific objective such as peak shaving, contingency control, or frequency control. DR can be automated or driven by flexible electricity tariffs. Examples of DR include: slowing down or stopping production at an industrial operation at certain times, shutting off lights, or increasing thermostat temperatures so the air conditioners do not run so frequently. In addition, many residential, commercial, and industrial technologies offer high DR potential because they contain an element of energy storage (e.g., electric water heaters, space heating, cold storage)

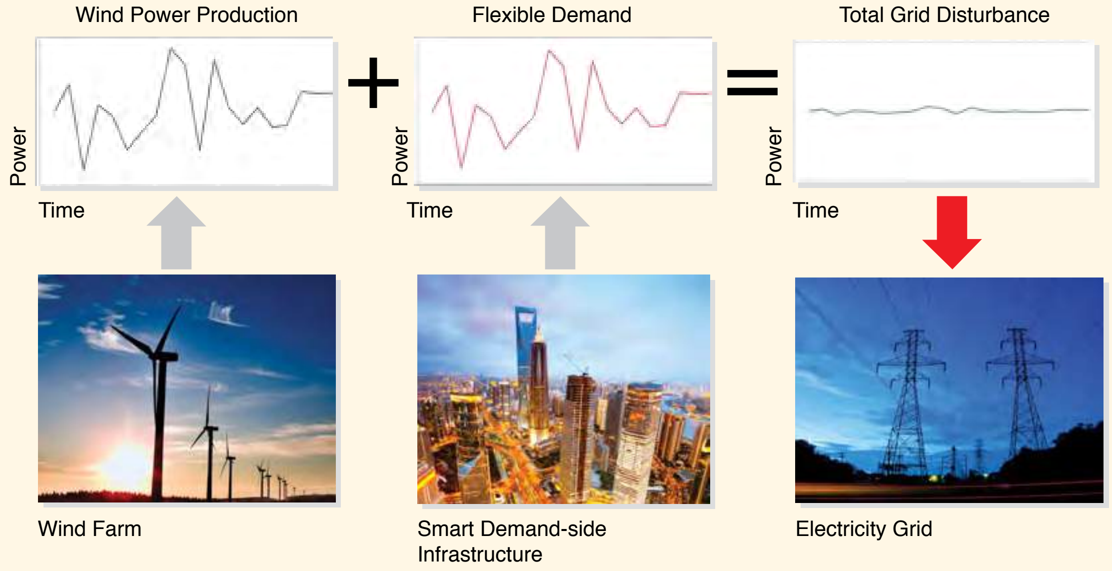
FIGURE A4.1
Demand-Side Management Applications



Source | Adapted from Kirby 2006.

FIGURE A4.2

Automated Demand Side Responses



Source | *Adapted from Ecofys.*

or the potential to shift in time energy requirements of energy-intensive processes (e.g., electrolysis, cement and paper mills, electric boilers, and electric arc furnaces; ECOFYS, Papaefthymiou, Grave, & Dragoon 2014). Automated DR or “smart DR” programs take advantage of new information and control technologies to enable two-way communication with loads that can be controlled in real time.

DR can reduce the need for additional investments in generation and T&D by reducing generation capacity needs. This has the potential to change the demand profile to accommodate the variability of the VRE output (i.e., by ramping down demand to reduce load and ramping up demand to absorb excess generation). In this way, DR effectively simulates the balancing and regulation reserves contributions from traditional assets, helps reduce the need for additional generation reserves and improves system efficiency.

DR is considered a cost-effective flexibility alternative.[48] Utilities pay for DR capacity because it is typically cheaper and easier to procure than generation capacity or storage. However, DR is limited by its inability to inject power to the grid and the logistical challenges of scaling the resource through an aggregated, coordinated response (i.e., getting all devices to adhere to a common communications platform). Achieving coordinated operation of all devices available for DR to act as a single, large megawatt “virtual power plant” requires complex control and communication technologies. Restrictions related to users’ data protection that can affect the ability to predict the load further complicates the task.

Some promising pilot programs in several countries (Capgemini 2008; GSMA 2012; RAP 2013) and new technology adaptations have proven that DR can be reliable for balancing services (regulation and load following) at a small scale. Important issues are the education and compensation of consumers to incentivize their participation in the power system as ancillary service providers. The value of ancillary services at high shares of VRE may need to be evaluated in each country, and compensation schemes or ancillary service markets should reward the speed and accuracy of the response.

ENDNOTE

[48] Some studies (Western-Governors’-Association, 2012) suggest that DR is more cost effective than other VRE integration solutions.

GLOSSARY

Active power: the component of the total power that can be used to generate work.

Adequacy: power system's ability to meet demand in the long run, assuming the regular day-to-day and season-to-season fluctuation in demand and supply (Benedikt 2006).

Automatic Generation Control (AGC): automatic control system that uses real-time data such as frequency, status, and generation of different units to adjust their power output in order to optimize operations and maintain power system frequency within prescribed levels.[49]

Balancing Area: collection of generation, transmission, and loads within the metered boundaries of a Balancing Authority. The Balancing Authority maintains load-resource balance within this area (NERC 2013). In a balancing authority area, the total of all generation must equal the total of all loads, as supplemented by electrical imports into and exports out of the area (NREL).

Balancing Reserves or Load Following: capacity used to correct anticipated imbalances on the system; similar to regulating Reserves, but with a slower response.

Base-load Generating Plants: power plants usually committed and dispatched at constant or near-constant levels with minimum cycling; often the sources of lowest cost energy when run at very high capacity factors (typically coal or nuclear power plants).

Capacity Credit: capacity of conventional plants displaced by VRE sources, whilst maintaining the same degree of system security.

Capacity Factor: ratio of the actual output of a power plant over a period of time to its potential output, calculated by taking the total amount of energy the plant produced during a period of time and dividing by the amount of energy the plant would have produced at full capacity, if it were possible for it to operate at full nameplate capacity indefinitely.

Characteristic Timescale: the span of time within which significant variability for power system integration occurs.

Combined Cycle Gas Turbine (CCGT): power plant arrangement where the waste heat from a gas turbine "topping" generator is used to generate steam to power the "bottoming" steam turbine.

Congestion: shortage of transmission capacity to supply demand characterized by generators running at full capacity and proper efficiency that cannot serve all customers.

Contingency Reserves: services sufficient to cover a many-megawatt, sudden, unplanned trip or disconnect of a large generator or transmission line to maintain system balance. Contingency reserves are generally split between spinning and non-spinning reserves and contingency requirements are usually based on the largest single hazard (generator or transmission capacity; NREL).

Cycling: repeated changes in electric load levels, including on/off and load variations, in response to changes in system load requirements; usually occurring during starts (hot, warm, and cold as exemplified in Figure 1.1), trips, shutdowns, load follows, and base-load operations.[50]

Direct Normal Insulation: solar radiation received per unit area by a surface that is always held perpendicular to the rays that come in a straight line from the direction of the sun at its current position in the sky.[51]

Dispatchability: ability of a generating unit or another source of power to vary its output on demand.

Dispatching: refinement of the scheduling process and relates to the real-time control of all generation and transmission resources that are being used and/or are available to meet demand requirements, recognizing the operational priorities of safety, security, and economy.[52]

Fixed-tilt Photovoltaic: photovoltaic (PV) modules mounted on a fixed structure kept at a fixed angle that it is calculated depending on the latitude of the location to maximize energy output. Solar panels should always face south when located in the northern hemisphere, or north if located in the southern hemisphere. In some fixed tilt panels, tilt can be adjusted seasonally to boost energy production.

Flexibility: ability of the system to maintain power supply despite quick changes in supply or demand.

Governor: device that measures the rotating speed of conventional generators and is used to increase the speed or reduce it in response to a change in frequency in the power system.

Greenhouse Gases (GHGs): gases that are released into the atmosphere as a result of natural activities such as volcanic eruptions, etc. and human activities such as combustion of fuels in transportation, industrial processes, energy generation, etc. Based on the heat-trapping properties of the gases, they are quantified as equivalents of CO_2 (i.e., CO_2e) using a metric known as Global Warming Potential (GWP). The GWP value of a gas indicates how long it remains in the atmosphere and how strongly it absorbs energy. CO_2 has a GWP value of 1 and serves as a baseline for comparing other GHGs. Gases with larger GWP value cause more warming. As an example, the 100-year GWP for methane gas is 21, which implies that it will cause 21 times as much warming as an equivalent mass of CO_2 over a 100-year period (EPA).

Liquefied Natural Gas (LNG): natural gas that has been compressed to liquid form to allow its storage or transport.

Net Load: difference between total/gross load and VRE generation.

Non-spinning Reserve: generation and responsive load that is offline but can be fully responsive within 30 minutes, and can be used to help manage generation variability and uncertainty for time frames that exceed 10 minutes (load following; NREL).

Operating Reserves: non-standard and widely varying term referring to additional generating capacity available to the system operator within a short interval of time capable of moving up or down for keeping a balance between supply and demand, stabilizing the transmission system in case of supply disruption, and maintaining the power quality on an economical basis in any competitive electricity market environment (Pirbazari 2010). Operating reserves can be divided in regulation, balancing (load following), and contingency reserves, depending on their response speed and frequency of use.

Passive Distribution Networks: grids designed to accept bulk power from a transmission system and distribute to customers without local coordinated control of voltage, flows, and fault levels.

Peaking Plants: plants with low capital cost and high or very high fuel costs used sparingly during extreme peak periods of demand.

Primary Reserve: primary control operating reserve used following disturbances to stabilize the system frequency within a few seconds. In modern power systems, primary reserves generators are controlled by active governor control.

Ramp: change in generation output over a specified unit of time.

Reactive Power: portion of power flow that is temporarily stored in the form of magnetic or electric fields, due to inductive and capacitive network elements, and then returned to source. Reactive power flow is needed in an alternating-current transmission system to support the transfer of real power over the network.

Regulating Reserves: operating reserves used to correct fast, frequent changes in load and generation, and any differences from forecasted conditions.

Regulating Reserves: capacity devoted to providing a fast up and down balancing service (NREL).

Renewable Energy: energy generated from resources that are continually regenerated over a short timescale such as sunlight, wind, rain, tides, waves, and geothermal heat.

Reserve Margin: total capacity installed divided by peak demand. According to NERC standards, the reserve margin should be higher than 12% to avoid potential problems in the grid.

Response Time: time in seconds within which a flexible device can provide maximum power output with applications. Storage devices with fast-response times of less than five seconds are used for balancing applications, and those with nearly instantaneous response are used to provide frequency regulation.

Scheduling: assignment of generation to meet anticipated demand.[53]

Scheduling: practice of ensuring a generator is committed and available when needed, as well as referring to the scheduling of imports into and exports out of a balancing area (NREL).

Secondary Reserves: operating reserves used to bring frequency to nominal value once primary reserves have stabilized frequency, and generally controlled by AGC systems in modern power systems.

Simple Cycle Gas Turbine or Open Cycle Gas Turbine (OCGT): power plant arrangement where the waste heat from a gas turbine power plant is vented (rather than combining with a bottoming steam cycle as in a CCGT configuration). Gas turbine systems operate on the thermodynamic cycle known as the Brayton cycle in which atmospheric air is compressed, heated, and then expanded by an expansion turbine.

Spinning Reserve: generation and responsive load that is online, can begin responding immediately, and is fully responsive within 10 minutes.

Spinning Reserves (or primary contingency reserves): grid-synchronized assets—usually natural gas-fired combustion turbines or large capacity reciprocating engine generators—with the ability to ramp up to full capacity and be dispatched within 10 minutes.

Supplemental Reserve: generation and responsive load that is offline but can be fully responsive within 10 minutes to replace spinning reserve that has been activated in response to a contingency or other power system need (NREL).

Thermal Energy Storage (TES): thermal energy storage technology used in CSP plants makes use of a two-tank salt system ("hot" and "cold" tanks) that store liquid salts separately. In a direct system, salt flows from the cold tank to the solar receiver, is heated, and enters the hot tank. During power generation, hot salt flows to the steam generator and returns to the cold tank. In an indirect system, the hot salt discharges through a heat exchanger to heat the heat transfer fluid (HTF) and then enters the cold tank. Charging occurs with the opposite flows (Zhiwen Ma).

Turn-Down Ratio: lower limit (as a percentage of the rated capacity) at which an engine or turbine can be operated.

Variable Renewable Energy (VRE): renewable energy generation assets that are based on sources that fluctuate during the course of any given day or season (IEA 2013). In this report, the term mainly refers to wind and solar (PV, Concentrated PV [CPV], and CSP without storage) generation.

ENDNOTES

[49] http://etap.com/energy-management-system/automatic-generation-control-software.htm

[50] http://www.wecc.biz/committees/BOD/TEPPC/External/0610-RealCost_on-off_cycling.pdf

[51] http://www.3tier.com/en/support/solar-prospecting-tools/what-direct-normal-irradiance-solar-prospecting/

[52] http://www.eirgrid.com/media/Dispatch%20and%20Scheduling%20Processes%20-%20December%2009.pdf

[53] http://www.eirgrid.com/media/Dispatch%20and%20Scheduling%20Processes%20-%20December%2009.pdf

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