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A WORLD BANK STUDY

Operating and Planning Electricity Grids with Variable Renewable Generation

REVIEW OF EMERGING LESSONS FROM
SELECTED OPERATIONAL EXPERIENCES
AND DESKTOP STUDIES

THE WORLD BANK

Marcelino Madrigal and Kevin Porter

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THE WORLD BANK
Washington, D.C.

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1 2 3 4 16 15 14 13

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ISBN (paper): 978-0-8213-9734-3

ISBN (electronic): 978-0-8213-9736-7

DOI: 10.1596/978-0-8213-9734-3

Cover photo: © iStockphoto

Library of Congress Cataloging-in-Publication Data

Operating and planning electricity grids with variable renewable generation : review of emerging lessons from selected operational experiences and desktop studies / Sustainable Energy Department, The World Bank.

p. cm.

Includes bibliographical references.

ISBN 978-0-8213-9734-3 (alk. paper)—ISBN 978-0-8213-9736-7 (electronic)

1. Energy development. 2. Renewable energy resources. 3. Power resources. 4. Electric utilities. 5. Sustainable development. I. World Bank.

HD9502.A2O62 2012

333.793'2—dc23

2012035604

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Acknowledgments

The paper is a result of a team of World Bank staff and consultants. The task team leader for this activity was Marcelino Madrigal (senior energy specialist) of the Sustainable Energy Department Energy unit (SEGEN). The main authors of the report are Marcelino Madrigal and Kevin Porter (consultant from Exeter Associates, Inc). Kevin Porter would like to thank Sari Fink and Jennifer Rogers of Exeter Associates for their contributions and to Lu Hong of The Energy Foundation and Andrew Mills of the Ernest Orlando Lawrence Berkeley National Laboratory for their assistance on various sections of the paper. Miguel Ortega-Vazquez (Assistant Professor, University of Washington) provided inputs on the status of research on variable generation's implication to short-term reserves. Assistance was also provided by Ruchi Soni (Junior Professional Associate, SEGEN). The team would like to thank peer reviewers Vladislav Vucetic, Dejan R. Ostojic, Leiping Wang, and Leopoldo Montanez, all from the World Bank, for their contributions to the paper.

This work was carried out under the overall leadership of Vivien Foster, manager of the Sustainable Energy Department Energy unit and benefited of guidance and support from Marianne Fay, Chief Economist of the World Bank's Sustainable Development Network and the Green Growth Development Platform.

The work is a continuation of the department's work to increase Bank's and client counterparts' understanding of the barriers and solutions to overcome renewable energy scale-up.

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Abbreviations

AGC	automatic generation control
BPA	Bonneville Power Administration
CHP	combined heat and power
CO ₂	carbon dioxide
CSP	concentrating solar power
dena	<i>Deutsche Energie-Agentur</i> (German Energy Agency)
DNI	direct normal irradiance
EENS	expected energy not served
EEX	Energy Exchange
EMS	Energy Management System
EnLAG	Power Grid Expansion Act
ERCOT	Electric Reliability Council of Texas
EU	European Union
FIT	feed-in tariff
FLM	flexible line temperature management system
FOR	forced outage rate
GDP	gross domestic product
GE	General Electric
GT	gas turbine
GW	gigawatts
GWEC	Global Wind Energy Council
GWh	gigawatt-hour
HVDC	high-voltage DC lines
IEA	International Energy Agency
ISO	Independent System Operator
km	kilometers
kV	kilovolt

LDC	load duration curve
LNG	liquefied natural gas
LOLE	loss of load expectation
LOLP	loss of load probability
MWh	megawatt-hour
NERC	North American Electric Reliability Corporation
NOAA	National Oceanic and Atmospheric Administration
NREL	National Renewable Energy Laboratory
NSCOGI	North Sea Countries' Offshore Grid Initiative
NWP	numerical weather prediction
OMEL	<i>Compania Operadora del Mercado Espanol de Electricidad, S.A.</i>
PV	photovoltaic
REE	<i>Red Electrica de España</i>
RFP	request for proposals
SCADA	Supervisory Control and Data Acquisition
SEGEN	Sustainable Energy Department Energy unit
SEGS	Solar Energy Generating System
TSO	transmission system operator
TWh	terawatt-hours
VOLL	value of lost load

Executive Summary

The development of wind- and solar-generating capacity is growing rapidly around the world, driven mainly by strong government support of various policy goals such as environmental sustainability and energy diversity. But integrating wind and solar generation (also referred to as variable generation) into grid operations is challenging: since wind and solar generation only occur when wind and solar resources are available, their output is not controllable. Grid operators are accustomed to dealing with variability, but primarily on the load side. The challenge is that higher levels of wind and solar generation add both variability and uncertainty.

Several countries—notably Denmark, Germany, Portugal, and Spain—are providing real-world experience in integrating high levels of variable generation, primarily wind power. In addition, several integration studies have modeled and simulated the addition of large amounts of wind, and to a lesser extent, solar generation to the grid. Such studies provide valuable information on the expected impacts of high levels of variable energy generation and potential strategies for successfully integrating variable energy generation into the system. These studies look at the technical operational impacts of integrating these resources into the systems and the potential technical and economic implications to system operations, notably short-term, reserve-related costs. Globally, variable renewable generation sources still represent mainly an energy and not a capacity resource. While their contributions to capacity or “firm” power and associated costs are different from those of conventional power sources, variable renewable generation technologies can contribute to long-term system adequacy and security. Several lessons learned can be gleaned from both operating experiences and integration studies.

What has been learned so far? Variable generation can be integrated successfully, but not without changes to the existing practices of grid operations and management as the amount of variable generation increases. Most experiences to date have been with integrating wind generation. Less is known about solar integration.

Is there a maximum amount of variable generation that can be technically incorporated? To date, no integration study has found a maximum technical limit of variable generation capacity that can be accommodated. The main limitation

will be the cost and the time it will take to adapt grid operational practices. This includes the amount of additional short-term reserves a grid operator may need to manage variability and uncertainty, potential changes in operating procedures and mitigation strategies, and the time necessary to learn from experience and implement appropriate responses, all to ensure that the system and renewable generation additions perform reliably.

How much variable generation capacity can we manage? Broadly speaking, though, the ease or difficulty of a country or region in integrating variable generation will depend on the geographic diversity of planned or operating wind and solar projects, whether the existing generation mix is flexible in starting and stopping operations quickly, the geographic size and the amount of load and generation a balancing area has, and whether there is available transmission capacity in the balancing area or interconnections to surrounding regions or countries. Countries and regions have incorporated significant variable generation capacity without one or more of these factors, but they may need to incorporate new or revised operating strategies sooner.

How much is the additional cost to system operations—integration costs—with variable generation? The operational costs to integrate wind power are nonzero to grid operators, and generally increase as the ratio of wind generation to conventional generation or peak load increases, with some reports suggesting that the rise is nonlinear as wind penetration increases. Wind integration studies performed to date, however, suggest that the projected costs to integrate wind are between \$1 per megawatt-hour and \$10 per megawatt-hour depending on the share of wind power in the system. In the United States results from more than 10 studies further suggest that costs are often below \$5 per megawatt-hour for wind shares up to 20–30 percent in terms of capacity share of wind. Separately, the International Energy Agency (IEA) found that balancing costs range from \$1 per megawatt-hour to \$7 per megawatt-hour, when wind energy output is 20 percent of total demand. Integration costs refer only to costs related to impacts on system operation aspects, such as the need for different forms of short-run reserves of variable generation. These costs do not include subsidies or other additional costs (for example, transmission costs) that may be necessary to support such technologies.

How can costs to system operations be determined? Integration studies are conducted to determine the impact on system operations of different amounts of variable renewable energy. The studies usually use grid and production simulation models to simulate the dispatch of the systems with variable power generation. The basic approach is to simulate the system with variable sources and compare the results—short-term dispatch costs—when a simulation considering supply from variable sources is replaced by a perfectly predictable and controllable source. Integration studies are data intensive and require appropriate models. For simulation to be meaningful such studies require data on the variable resources assessment and the expected power output for every dispatch time period in a year. To capture the impact of sources such as wind and solar power, the time period should at least be on the order of a few minutes to half an hour. Production

simulation models need to capture not only the variability of renewable power sources but all constraints in the system such as transmission limits and the response characteristics of the rest of the generation system.

When and how should an integration study be done to estimate the short-term reserve costs of renewable energy? Operating an electric power grid is a complex, multistep process of forecasting expected load and generation availability and making changes and adjustments as it gets closer to real time. Adding variable energy generation adds uncertainty and unpredictability that grid operators will need to manage. Experience and desktop studies seem to suggest that small amounts of variable energy generation (<10 percent of total demand) can be handled, without significant cost implications, using a “connect and manage” approach—interconnecting variable energy generation and curtailing or redispatching variable and other generation as needed—if a utility or grid operator has some resources such as flexible generating resources, adequate transmission, and geographically diversified wind and solar projects. At higher levels of variable generation, or if a grid operator does not have some of these characteristics, determining the impact of variable generation requires conducting appropriate variable generation integration studies.

A variable generation integration study typically identifies the operational and reliability issues that stem from increasing levels of variable energy generation. At each level of wind and solar generation studied, variations in production costs, changes in reserve requirements, and the flexibility of existing generation assets to operate at different set points are evaluated. Variable generation integration studies are data and labor intensive and can take from a few months to more than a year to compile. Data needed for a variable generation integration study include at least one year (and preferably multiple years) of high-resolution (10-minute sample) time-synchronized wind, solar, and load data to capture the variability of load and wind that impacts short-term reserves. Load forecasts for multiple years are also needed to compare the performance of load forecasts, along with sub-hourly load and generation data (minute by minute, over 10 minutes) for analysis of periods of interest (high wind, high load, high wind/low load, high solar/high load, high solar and wind/high load, and so on) and to determine the subhourly requirements of ancillary services such as different types of short-term reserves. The study will need to prioritize which impacts are likely to be more important than others. For instance, implications for transmission adequacy could be immediate while impacts on reserve may manifest only at higher levels of variable generation integration.

Besides impacts on short-term reserves, what are the other operational impacts and challenges that operators need to be aware of? In addition to the potential impacts on short-term reserves at higher penetration levels, variable power generation can have other impacts on system operations that require appropriate responses. For instance, besides the power output uncontrollability characteristics of these sources, their frequency and voltage are different from those of conventional power sources. For instance, older wind power generation technologies are

sensitive to voltage reductions, which require their disconnection from the grid. Newer technologies are able to cope with voltage depression and remain connected to the system. Similarly, given their limited controllability, wind and solar sources contribute much less to frequency control in the system. While these limitations can become more relevant at higher penetration levels (<10 percent), they could pose additional challenges at higher penetration levels or if the system (for example a small or islanded system) does not have other sources of controllable generation and interconnection or already has limited frequency control capabilities. The mass of rotating generators is important to maintain system stability to sudden faults that choke the transport of power in a system. As the level of supply from renewable energy increases—whose generation units tend to have smaller rotating masses which contribute less to system inertia—the potential impacts on system stability need be assessed. To date there is no operational or desktop study that points to this as a major hurdle; however, research is under way on systems that may use a significant amount of renewable energy (>30–40 percent). The goal of such research is to identify challenges and potentially improve the capability of variable renewables with new forms of coordinated control actions.

Do variable renewables provide long-term supply security? Variable power sources such as wind and solar power continue to mostly represent an energy resource at current penetration levels around the world. While at different scales and costs than “firm” conventional power sources, they contribute to ensure long-term demand is met adequately. “Firm” or “base-load” power refers mostly to sources that are worthwhile operating continuously to serve large amounts of demand at the lowest cost. Both base-load and peak-load plants are required to make sure the system meets demand with given supply adequacy and security standards—which can be expressed by long-term reserve margins or other probabilistic measures. Variable power sources can also contribute to ensuring supply adequacy standards are met; however, their contribution will be limited by the resource energy profile and how it coincides with demand patterns and other generation resources in the system. For instance, wind power output tends to be lower during peak demand periods and for this reason its contribution to meet peak-reserve margins will be limited if compared to conventional power sources whose availability at peak can be guaranteed with much higher certainty or to a solar power whose peak production may more often coincide with peak demand. Adequacy requirements are different in all systems and large amounts of diversified variable power sources will contribute to ensuring technical supply adequacy standards at the system levels—variable power plants do not need be backed up individually to ensure long-term adequacy. Similar to the implications to grid operations, while large amounts of variable power sources can contribute to ensuring long-term supply adequacy is met, the main limitations will be cost—and affordability—and the time it will take to adapt system operations and planning.

How can planners determine long-term investment needs to ensure adequacy standards are met while increasing the share of variable renewables? Grid operators and

planners are already developing methodologies to understand the contribution of variable renewable power sources to system adequacy. The trend is to use probabilistic modeling approaches to determine what the equivalent of a certain variable power source is in terms of “firm” capacity (comparable power plan) and on how such contribution impacts overall system adequacy to meet demand. Long-term adequacy assessments by systems with already large penetrations of variable power sources—wind power especially—are already incorporating such methodologies in their resource adequacy assessments. These assessments, including other research literature, report that the contribution of wind power largely depends on its diversity and interaction with the demand profile and other generation in the system. But it is evident that the contribution of wind power to firm capacity is limited if compared to its nameplate capacity. For instance, though studies report that at low penetrations of wind, contribution to firm capacity can be up to 40 percent of its nameplate capacity, such contribution can decline to levels of 15 percent or even 10 percent of the installed wind capacity as the share of wind power in the system increases to levels above 30 percent. Contributing more to supply adequacy will always depend on the diversity of resources by the combination of various options such as wind, solar (with and without storage), hydro, and other conventional resources. Using these evolving methodologies, planners need to adapt old planning practices that, with the exception of some well-established practices in planning with hydropower, do not adequately handle the uncertainty of variable power sources.

What available strategies are used to integrate variable generation into system operations? The multitude of integration studies and experience gained to date with integrating variable generation is giving rise to a number of acknowledged strategies and solutions for variable generation integration. The strategies that need be deployed largely depend on the amount of renewables being integrated. These include forecasting wind and solar generation; implementing or revamping existing grid codes to ensure wind and solar generation stay in operation during system faults or low voltage; expanding balancing areas, either virtually or through the consolidation of multiple balancing areas; developing subhourly markets; considering new types of reserves for managing the variability and uncertainty of variable generation; constructing additional transmission capacity; making existing generation more flexible or installing more flexible generation; implementing demand response programs; and taking advantage of new advances in wind technology that can provide reactive power, frequency control, certain types of ancillary services, and system inertia.

Each of these possible options should be viewed as a menu; picking a strategy or set of strategies requires a full assessment to determine the lowest-cost options. For example, it would not be desirable to install storage systems to solve a variability problem whose magnitude can be solved simply by improving forecast and changing dispatch functions. As the amount of renewables increases, the lowest-cost options to improve flexibility should be exhausted before more expensive options are explored. For instance, if forecasting has already been

implemented, and further diversity of resources to smooth out variability cannot be achieved with transmission (for example, small geographical area), flexibility may require investing in other options such as fast generation options or storage to directly address the variability impacts.

Clearly identifying potential operation problems will require proper network integration studies, and implementing the solutions will also require gaining some technical capacity and institutional and regulatory rearrangements whose nature and magnitude will largely depend on the status of infrastructure, operational practices, and expected levels of variable renewables in the particular system. Table O.1 provides a summary of the potential preconditions in these areas that could arise in the context of many systems in the early stages of integrating renewables.

Table ES.1 Strategies to Manage Variability of Renewables in System Operations and Some Prerequisites for Their Application and Effectiveness

<i>Strategy</i>	<i>Description and prerequisites: technical, institutional, or regulatory</i>
Forecasting	<p>Forecasting is essential once variable generation is beyond small penetration; will help minimize fuel and short-term reserve needs.</p> <p>As with demand forecast, it needs to be used to influence dispatch operations at different time frames: day ahead, hours ahead, and tens of minutes ahead. It is critical to define the responsibility of renewable providers with regard to providing forecasting or key data necessary to grid operators and dispatch centers to prepare or improve forecasting based on the data or forecast already provided by the renewable energy suppliers. These responsibilities can be clearly defined as part of the operational rules usually inscribed as part of the grid code.</p>
Subhourly markets	<p>This means shorter market clearing periods to incorporate updated variable generation forecasts and, with that, better access flexibility from existing generating units or other ancillary services established (for example, balancing).</p> <p>Subhourly markets can also be implemented on vertically integrated systems, where short-term dispatch is not necessarily used to price spot energy transactions. It will be effective at managing the impacts of variability as long as forecasting is influencing dispatch. In systems where short-term dispatch serves the function of price determination for energy exchange, subhourly markets have traditionally been established and their design and definition requires a wider consultative process with all stakeholders. Market rules regarding intraday price determination and billing may need be adjusted accordingly.</p>
Shorter scheduling intervals	<p>Submitting schedules closer to real time will allow for more accurate forecasts of wind and solar generation, but may lead to higher costs from the increased starting and stopping of conventional power plants.</p> <p>These require better information and telecommunication systems and well-structured processes for linking short-term operations with real-time dispatch in the Supervisory Control and Data Acquisition (SCADA) and Energy Management Systems (EMS) systems. It also requires discipline in maintaining short-term operations and real-time schedules, always on time.</p>

(table continues on next page)

Table ES.1 Strategies to Manage Variability of Renewables in System Operations and Some Prerequisites for Their Application and Effectiveness *(continued)*

<i>Strategy</i>	<i>Description and prerequisites: technical, institutional, or regulatory</i>
Consolidating balancing areas	<p>Larger balancing areas (operational regions) improve both load diversity and the diversity of wind and solar generation, reducing overall variability. Larger balancing areas also can access a deeper stack of generation to help balance the variability of load and generation resources.</p> <p>These will be effective to the extent that variability in the different areas is complementary with other areas. This tends to happen only in systems where geographical areas are large and span across varied climatological and topological conditions that impact renewable resources availability. For instance, systems in small territories or islands may not benefit largely from this strategy.</p>
Flexible resources	<p>Higher amounts of variable generation will result in the need for flexible generation; that is, for generation to increase or decrease operations more quickly and over a wider operating range, as required by variable renewable and demand variation. Flexibility can come from many types of generation or nongeneration sources such as storage.</p> <p>If a system is already endowed with adequate operating and planning reserves and these resources have the capability to respond quickly to wind or solar events, the incentives or regulated approaches make sure these resources become available when needed. If a system is already dedicatory in reserves, conventional power sources will mostly only add energy to the system even at high penetration levels. In such cases and at high penetration levels of renewables, adding fast-responding units may require carefully planned and deliberated action.</p>
Grid codes	<p>These are used to define the electrical performance requirement of variable power generation (mainly voltage and frequency), the operational and dispatch rules, and the interconnection to grid planning aspects</p> <p>Grid codes are as good as their enforcement. It is critical that grid codes are actually enforced and appropriate tests are carried out strategically to ensure old and new technologies comply with required performance standards.</p>
Improving planning practices	<p>Technical planning to ensure adequacy of transmission and adequacy of supply to continue meeting security and adequacy standards as shares of variable renewables increase.</p> <p>Planning practices need be adjusted to ensure the contribution of renewables to supply adequacy to the system and that cost implications are rightly assessed (not over- or underestimated). As variable renewable shares increase, planning needs to take a look also at potential future implication on short-run operations to properly identify the most cost-effective solutions</p>
Demand response and demand side management	<p>This refers to changes in demand to direct requests from system operators or different forms of price incentives or disincentives.</p> <p>Demand response depends on many factors such as type of consumers being targeted and types of instruments (price incentives/disincentives or quotas). The natural progression of a demand response system would be to fix any evident pricing distortions, introduction of time-differentiated tariffs, and any other efficiency pricing intervention that tends to flatten peak demand such as pricing of overconsumption of reactive power. Real-time pricing is the next step and requires proper metering and information systems similar to demand time of use pricing. Interruptible tariffs that offer rebates of price reduction are also other potential mechanisms.</p>

Source: World Bank data.

The Challenges of Integrating Wind and Solar Generation

Introduction

The development of wind- and solar-generating capacity is growing rapidly around the world as policy makers pursue various energy policy objectives. Among several advantages, wind and solar generation:

- Provide emission-free electricity
- Can be added in modular increments over time, that is, in tens or hundreds of megawatts as compared to large conventional plants
- Can be brought online relatively quickly once associated environmental permits are given
- Add fuel diversity to a generation portfolio
- Are cost competitive with conventional fuels in some cases
- Can reduce dependence on conventional fuels and help contribute to fuel cost certainty.

But integrating wind and solar generation (also referred to as variable generation) into the grid is challenging, as wind and solar generation only occurs when wind and solar resources are available, and as such, are said to be not dispatchable (if dispatch is understood as varying output at will by varying fuel inputs). As will be explained later, the limitation of wind or solar power is mostly a control and not dispatchability limitation. The electric grid is designed to manage variability on the load side with conventional generation that can be adjusted as needed to meet load variability. Therefore, the electric grid is used to dealing with variability, but primarily on the load side. The challenge is that higher levels of wind and solar generation add both variability and uncertainty, in that it is uncertain how much and when production will occur from variable generation (NERC 2009).

The addition of wind and, increasingly, solar capacity is providing some real-world lessons in how to successfully integrate variable energy generation. Moreover, several studies (known as integration studies) modeling and simulating

the addition of large amounts of wind, and to a lesser extent, solar generation to the grid have also provided some documentation on the potential impacts of high levels of variable energy generation and potential strategies for successfully integrating variable energy generation. This paper will describe the challenges in integrating wind and solar generation, the lessons learned, and recommended strategies from both operating experience and integration studies. Case studies on the experience with wind and solar integration in China, Germany, and Spain are also included in this paper.

The paper is organized as follows. This section summarizes worldwide wind and solar development, the challenges in integrating wind and solar generation, and some of the lessons learned from studies designed to evaluate the impact of higher levels of wind and solar generation and also from the operational experience in some countries with larger amounts of renewable energy. The second section summarizes some of the solutions for incorporating higher levels of wind and solar capacity into short-term system operations. This section also explains basic methodologies to implement system operations studies to understand the impacts of variability in system operation. The third section explains the contribution of variable renewables to long-term supply adequacy—commonly called “firm” power—and the relationship of this to long-term reserves; it also explores how these issues can be incorporated into long-term planning or adequacy assessments.

Wind and Solar Development

Worldwide installed wind capacity was nearly 200 gigawatts as of the end of 2010, with projects in operation in 83 countries (REN21 2011). It is projected that 1,000 gigawatts of wind will be in operation worldwide by the end of 2020 (GWEC 2011). China leads the world in installed wind capacity with 44 gigawatts installed, followed by the United States, Germany, and Spain (see figure 1.1)

Solar use is also growing exponentially, with solar photovoltaic (PV) more than doubling in 2010 and installed in over 100 countries. About 17 gigawatts was installed around the world in 2011, and about 40 gigawatts total of solar PV was installed worldwide—more than seven times the solar PV capacity in 2005. Decreasing costs of solar PV and strong policy support were among the primary drivers for the rapid increase in solar PV systems. About 80 percent of solar PV installations in 2010 were located in the European Union (EU), and indeed, Europe added more solar PV capacity than wind capacity in 2010 for the first time. In fact, Germany installed more solar PV in 2010 than the world did in 2009, and has 44 percent of the world’s PV total installed capacity, as indicated in figure 1.2 (REN21 2011).

Worldwide installed capacity of concentrating solar power (CSP) grew by 478 megawatts in 2010, resulting in a total of 1,095 megawatts worldwide. About 90 percent of CSP capacity is made up of parabolic trough plants. Spain

Figure 1.1 Leading Countries in Installed Wind Capacity, 2010

Country	MW	Percent
China	44,733	22.7
United States	40,180	20.4
Germany	27,214	13.8
Spain	20,676	10.5
India	13,065	6.6
Italy	5,797	2.9
France	5,660	2.9
United Kingdom	5,204	2.6
Canada	4,009	2.0
Denmark	3,752	1.9
Rest of the world	26,749	13.6
Total TOP 10	170,290	86.4
World total	197,039	100

Source: GWEC 2011.

Note: MW = megawatts.

and the United States are the two leading countries in the world for CSP-installed capacity. Another 946 megawatts of CSP capacity is under construction in Spain, with a total capacity of 1,789 megawatts expected in Spain by the end of 2013. About 1.5 gigawatts of parabolic trough and power tower projects are under construction in the United States, and power purchase agreements are in place for another 6.2 gigawatts. That said, the declining costs in solar PV are prompting some developers to switch planned projects from CSP to solar PV. Other countries in North Africa and the Middle East are interested in CSP, and China has plans to install CSP combined with cogeneration to provide electricity and space and/or process heat (REN21 2011).

Figure 1.2 Top 10 Countries in Solar Photovoltaic (PV) Capacity, 2010, by Percent

Source: REN21 2011.

Note: EU = European Union.

A number of countries are successfully integrating wind at high levels of penetration by energy, as indicated in table 1.1. Notably, the two countries with the most installed wind capacity in the world—China and the United States—have modest contributions from wind by energy penetration.

The Operational Challenges in Integrating Wind and Solar Generation

Wind and solar generation are dependent on the availability of wind and solar resources, not on the quantity of a fuel feedstock such as natural gas or coal. As such, wind and solar generation will be both variable and uncertain (how much output to expect and when), which subjects their dispatchability to accurate forecasting and highly limits their controllability (see box 1.1). Therefore, the ability of system operators to control these plants while simultaneously maintaining the power system's balance between load and generation is challenged (DeCesaro and Porter 2009).

The challenge of wind integration relates to variability and uncertainty of wind. The power grid is designed to handle some level of uncertainty and

Table 1.1 Leading Countries in Energy Penetration from Wind Energy (2009, unless otherwise indicated)

Denmark ^a	25%
Spain ^a	16%
Portugal	15.4%
Germany	6.4%
United States ^a	2.9%
China	0.7%

Sources: Chandler 2011; Diaz 2011; Eames 2011; Kahrl and others 2011; Wisner and Bolinger 2011.

a. 2010.

Box 1.1**Variable Renewable Sources: Dispatchable, But Not Controllable**

As generation may have to go offline because of mechanical issues or for periodic maintenance, all generation is variable to some degree. For wind and solar generation, variability is more pronounced because generation is dependent on the availability of wind and solar resources, and it cannot be stored as coal, oil, or gas. The output of variable generation changes according to the availability of the primary fuel (wind, sunlight, and moving water), resulting in fluctuations in plant output on all time scales. Thus, wind and solar generation cannot be controlled to the extent that conventional generation can be controlled, which can adjust output at will by adjusting fuel inputs through automatic controls. Wind and solar generation, however, can be dispatched to the extent they can be forecasted, albeit imperfectly and with uncertainty. Operators determine the outputs required by all generation to meet demand at different time frames before real-time operations. These time frames could be months, weeks, days, a few hours, or a few minutes before real-time operations. In this regard, operators can determine the output of wind and solar power (dispatch them) based on forecast and with that determine the residual demand that needs to be met by conventional generation—which they will be able to control in real time, when demand is finally supplied.

While the term *dispatch* sometimes is used to refer to the real-time action of controlling output at will (responses to output that take less than seconds to a few minutes), it is useful to make a distinction between dispatch and control to understand the actual limitations of variable power sources. With this in mind, operators are increasingly able to incorporate wind and solar power into their dispatch processes by means of forecasted values to set the power output values of these resources, while conventional source outputs are set to meet the residential demand in a least-cost fashion. Forecast of wind and solar power tends to be more accurate in the days- and hours-ahead time frames, which further facilitate dispatch. Recently, operators were working on improving forecasting for special fast ramp-up or ramp-down events created by sudden meteorological condition changes that have important impacts on balancing demand. In conclusion, to the extent that wind and solar power forecasts are accurate—as it happens with demand forecasts—these resources can be incorporated into day-ahead or intraday dispatch preparations even if they cannot be controlled the same way as other power plants in real time.

Source: World Bank data.

variability resulting from the variability of load, the uncertainty of load forecasts, and the uncertainty from the potential outage of generation or transmission facilities. In well-established and long-running power grids, though, there is a long history with load forecasts. Day-ahead load forecasts typically have an average error of 1.5 percent, increasing to 5 percent a week ahead. Demand variability is more regular and predictable, with predictable

daily and weekly patterns and seasonal demand for heating, cooling, and lighting, particularly in countries at higher latitudes. Demand variability is higher when customers respond to unexpected events such as cold or hot weather periods. Load uncertainty, therefore, is typically pretty small.

The power system is planned such that different types of generating resources can respond to load variability (for example, base load, intermediate, and fast start) and uncertainty with the load forecast is generally quite small. Uncertainty regarding generation or transmission outages is more discrete and is part of reliability (contingency planning) analysis, where contingency events are assessed for the impact on power grid operations (Chandler 2011). Ensuring that the system continues to deliver the needed electricity despite these various uncertainties requires redundancy in system components such as transmission and also generation reserves. For instance, despite the fact that load forecasting can be highly accurate a day ahead, system operators need to ensure that enough generation resources are available to respond to the difference between actual system load and the previous day forecast. This type of reserve can be broadly categorized as short-term operating reserves. Similarly, planned or unplanned generation or transmission outages and other longer-term (for example, seasonal and yearly) uncertainties of projected demand or resource availability (for example, hydropower) trigger the need for reserves. These reserves are determined mostly by long-term planning and maintenance scheduling assessments and can be broadly categorized as long-term planning reserves. The same generation facility can provide both short-term operating reserves and long-term planning reserves. When a system has deficits of long-term reserves, most likely it will also be short of short-term operational reserves. Long-term reserves are related to adequacy of the system meeting demand in future years. As with hydropower, variable renewable sources such as wind and solar power also contribute differently to long-term system adequacy. The contribution of variable renewable energy to long-term adequacy needs also has to be addressed (a future chapter in this paper elaborates on the issue).

At the operational level, the variability of wind and solar resources and the uncertainty of forecasting wind and solar power make them different from other generating resources. The weather patterns that drive wind generation differ across several time scales and are only loosely correlated with load. Therefore, while more complex to predict given evolving experiences, the uncertainty in wind or solar generation is more comparable to uncertainty in load than to uncertainties related to system outages which are more discrete and harder to predict. Different from wind or solar output or demand variations, generation or transmission outages could indeed be more accurately described as an intermittent event.

At small penetrations of wind, load uncertainty is still prevalent—and for that matter need for additional reserves will be low or negligible—but at higher levels of wind generation, wind forecasting becomes more important to ensure that electric reliability is maintained and that the balance between supply and demand

Box 1.2**What Grid Codes Can and Cannot Do**

Grid codes detail the technical requirements for electric generating plants to ensure reliable and safe operation of the electric grid. In several countries, grid codes have been implemented or modified to incorporate requirements for wind and solar power, such as providing reactive power and staying online for a minimum period of time in response to voltage drops or transmission faults and to make sure these resources—especially when connected at the distribution side—are visible to system operators by collecting and submitting power and other measurements to control centers. Complying with grid codes is vital to maintaining electric reliability—they set up technical performance or reliability standards for electricity grids, but they do not always define which resources are required to achieve these standards. While grid codes may specify the allowed frequency deviations that can happen due to a momentary lack of short-term reserves, grid codes do not usually specify the amount of reserves required to achieve such a performance standard. The needs for reserves and how these are procured and remunerated are usually handled by other instruments such as operational rules and ancillary service rules. With regard to renewable energy, grid codes also contain provisions for operations and planning rules such as exchange of forecast information and the process of requesting interconnection to the grid, respectively.

Source: World Bank data.

is preserved. Increases or decreases in net load (for example, load minus wind minus solar or wind power output), and the rate and frequency of these increases and decreases, is important. Assessing the combination of variability and uncertainty with higher levels of wind power is important to estimate possible impacts and to plan for any needed mitigation actions such as grid codes, flexible demand or generation capacity, or wind curtailment (see box 1.2) (Bai and others 2007).

The issue of how to incorporate and integrate wind power, and more recently solar power, has been studied frequently in recent years, through a combination of operating experiences and academic studies. There is more accumulated experience with wind than solar, although there are common implementation issues for both resources. Broadly speaking, though, the ease or difficulty of a country or region in integrating variable generation will depend on the following factors:

- *The geographic diversity of planned or operating wind and solar projects.* Output from wind and solar projects that are more spread out geographically will be smoother than output from wind and solar projects that are concentrated in a particular location.
- *The composition of the existing generation resource mix.* Having more flexible generation that can start up quickly and can ramp up and down quickly will make it easier to integrate larger amounts of wind and solar generation. Conversely,

having less flexible generation will make it more difficult to integrate wind and solar generation. Overall, the variability of wind power generation adds to the variability on the grid in most time scales, and a key question that wind integration studies must address is whether there is enough existing capability on the grid to manage that increased variability, or whether new sources must be added to manage it.

- *The size and depth of balancing areas.* Balancing areas are the physical operating areas that grid operators serve and, within that physical balancing area, must balance supply, demand, and interchange with neighboring balancing areas. Balancing areas are also known as control areas. Most small countries will have only a single balancing area. Larger countries may have different balancing areas for different regions, while sometimes balancing areas coincide with state boundaries. Larger balancing areas—achieved either through physically consolidating balancing areas or by using virtual mechanisms such as sharing energy imbalances and area control error—increase load diversity, which reduces the magnitude of the peak load with respect to installed generation capacity. Similarly, larger balancing areas help provide greater diversity for wind and solar resources, which smoothes wind and solar production and reduces the magnitude and frequency of extreme changes in wind production. Ultimately, this serves to reduce the number of hours during which the most expensive units in the dispatch queue will be operating, subsequently reducing the operating reserve requirement.
- *Transmission availability and interconnections with surrounding regions or countries.* Having strong interconnections with neighboring countries will allow the exporting of surplus variable generation or the importation of additional reserves, if necessary. Similarly, having a strong transmission grid will allow higher levels of wind and solar generation to be accommodated (DeCesaro and Porter 2009). Transmission is necessary to interconnect variable power sources of wide geographical diversity, which, in turn, help mitigate the impacts of variability.

Every country will be different in its ability to integrate wind and solar generation, based on its individual characteristics. Some countries will have large amounts of generating capacity and large balancing areas; others will be small or “islands” that are not connected with nearby areas. Demand, and the shape of that electric demand, will also vary by country. Some will have heavy industrial load that will be largely flat, while others have more commercial and residential loads that will vary by season and time of day. Some countries will also have stronger transmission and distribution networks than others.

This paper will discuss “lessons learned” with wind and solar integration, both from the academic literature and from operational practice; the estimated impact of wind integration (and solar, if data are available) on system reserves and integration costs; common strategies used to integrate wind and solar generation; future methods being considered to integrate wind and solar

resources; and the greater technical capabilities of newer wind technologies to help with system operations, including providing reactive power, system inertia, ramping control, regulation, and frequency control.

Understanding Electricity Systems' Operational Time Frames and the Impact of the Variability of Wind and Solar Generation

Variable generation integration studies typically divide grid operations into the following time frames: regulation, load following, and unit commitment. These terms differ between countries (for example, regulation is often called “primary reserves” in Europe, or unit commitment may be referred to simply as advance or day-ahead dispatch), but provide a useful framework for considering the potential impacts of wind and solar integration over multiple time frames, ranging from subhourly to hourly to over several hours or days. These terms are further explained below and illustrated in figure 1.3.

Figure 1.3 Power System Operation Time Frames

Source: Ela, Milligan, and Kirby 2011.

Regulation encompasses the period during which generation automatically responds to minute-by-minute deviations in load. Typically, a system operator will send signals to one or more generators to increase or decrease output to match the change in load. Regulation covers a time scale ranging from about several seconds to 10 minutes. Changes in load are typically not predicted or scheduled in advance and must be met with enough generation that is online and grid synchronized to ensure that changes in load are met. Typically, a small amount of generating capacity, or responsive load in some instances, is equipped with Automatic Generation Control (or AGC) to provide regulation services in the seconds-to-minutes time frame. AGC plays a major role in managing short-term uncertainty of variable generation and to mitigate some of the short-term impacts (that is, intrahour) associated with variable generation forecast error.

Load following includes periods ranging from 10 minutes to a few hours, during which generating units are moved to different set points of capacity, subject to various operational and cost constraints, and in response to increasing load (in the morning) or decreasing load (late in the day). Load following is generally provided by generating units that are already committed or those that can be started quickly, subject to constraints specific to the generating unit. Load following can be subdivided into spinning reserves, where generation is online and can respond quickly; nonspinning reserves, which can be offline but are able to respond quickly; and supplemental reserves that are offline and respond more slowly, and act to relieve the other reserves so they can be used again to manage other system events or imbalances between load and demand. Reserves that help in the load-following function are sometimes classified in terms of the speed in which they can be added to the system—for instance, 10-minute spinning reserves would mean generation reserves that can be brought online within 10 minutes of the request.

Unit commitment spans several hours to several days, and concerns the advance scheduling and committing of generation to meet expected electric demand. Unit commitment is also described by other terms such as “day-ahead dispatch,” “operations planning,” or “generation programming.” While the term is more broadly used in thermal-based systems, it also applies to systems with hydropower and other sources. The unit commitment function determines which generation units will be brought on or off within an hour to several days’ time frame to meet forecasted demand. Generation in the unit commitment time frame may require several hours, even days, to start up and increase to the preferred operating level. The length of the unit commitment time frame depends at least in part on the operating characteristics of the generation sources on the grid. It is at this time frame when some inflexibilities of fossil fuel generation need to be considered while programming generation dispatch for the next few days. Some of these inflexibilities include minimum off (cooling) or on times and the maximum number of shutdowns a unit should be exposed due to technical or efficiency constraints. Other restrictions such as power output ramp rates (that is, how fast a generator can increase or decrease output) also must be

accounted for. For thermal systems, it may be day-ahead or multiday ahead, while for hydro-based systems, it may be weekly or several weeks ahead, based on expected water availability. Therefore, planning the “right” level of unit commitment is important. Wind production is more uncertain in longer time frames, which may result in higher operating costs due to overcommitting generation as a result of underpredicting expected wind generation, or as a result of not having enough generation committed because expected wind generation is not available, resulting in the need for starting up generating units quickly or to engage in short-term market purchases (DeCesaro and Porter 2009).

Generation technologies have different response characteristics, which have made them more valuable than others in different operating time frames. For instance, gas turbines or hydropower can be very useful to quickly respond to regulation signals. On the other hand, older coal or other thermal power plants may not have the ability to quickly respond in this time frame, but are more valuable to provide stable levels of output during longer time frames (for example, daily, weekly dispatch). These characteristics will define how each generation unit can respond to different system needs in the different times frames, regulation, load following, and unit commitment (see table 1.2). For example, mostly any generation type will respond naturally to frequency fluctuation, but not all will be able to regulate their output unless they are equipped with Automatic Generation Control (AGC) equipment. On the load-following side, if the aggregated demand variation is too fast, some units (such as subcritical coal, nuclear) may not be able to respond in the desired time frame, while others (for example, a Gas Turbine GT) may be able to do so. In the unit commitment time frame, a day-ahead or intraday error in wind or solar forecast may impact importantly on the type of sources the system can pull off to balance the system. For instance, a pressurized fluidized bed combustion (PFBC) coal power plant may not be able to start up in the required time frame (2 hours), while a supercritical plant may be able to do it. The type of resources that the system requires to meet all variations will greatly depend on the variation of demand and generation and the

Table 1.2 Flexibility Characteristics of Some Generation Technologies

Type	Efficiency (%)	Load range (%) ^a	Ramp rate (% ^a /min)	Startup time (h)	
				Cold	Hot
Subcritical (50–1,000 MW)	36–38	25–100	8	4–8	1–1.5
Supercritical (50–1,000 MW)	40–46	25–100	8	4–8	1–1.5
AFBC (50–350MW)	~40	30–100	5–7	8–12	2–3
PFBC (70 and 350MW)	42–45	40–100	2–4	15	3
Simple GT (100 MW)	~ 40	75–100	10	0.2–1	—
CCGT (250 MW)	~ 45	50–100	10	5	2
IGCC (100–320 MW)	43–45	50–100	5	24	up to 48

Sources: Prepared with data from EIA and EPCOR.

Note: AFBC = atmospheric fluidized bed combustion, CCGT = combined cycle gas turbine, PFBC = pressurized fluidized bed combustion, GT = gas turbine, IGCC = integrated gasification combined cycle, MW = megawatts, h = hours, — = not available.

a. Percentage of maximum output.

quality of their forecasts and how these interact with the transmission system and overall producer to dispatch and control generation in real time.

Countries use different terminology in describing ancillary services needed to maintain grid reliability. In Europe, primary reserves assist with the short-term, minute-to-minute balancing and control of the power system frequency, and is equivalent in the United States to regulation (all of which are short-term reserves). Secondary reserves in Europe take over for primary reserves 10–30 minutes later, freeing up capacity to be used as primary reserves. Longer-term reserves in Europe are called tertiary reserves and are available in the periods after secondary reserves.

Table 1.3 compares these different definitions between Europe and the United States.

Summary of Findings from Variable Generation Integration Studies and Operational Experiences

This section summarizes the results of multiple variable generation integration studies, mostly from the United States and Europe. These studies include those prepared for the California Energy Commission, the California Independent System Operator, the New York Independent System Operator, the Independent Electric System Operator of Ontario, the Independent System Operator of New England, and the Electric Reliability Council of Texas (ERCOT). In addition, operating experience from grid operators with high levels of variable generation is also discussed, such as the Bonneville Power Administration in the United States and Red Elctrica of Spain.

Regulation

Again, regulation encompasses the period during which generation automatically responds to minute-by-minute deviations in load and ranges from several seconds to 10 minutes. To date, variable generation integration studies have

Table 1.3 Reserve Definitions in Germany, Ireland, and the United States

	<i>Short-term reserves</i>	<i>Medium-term reserves</i>		<i>Long-term reserves</i>
Germany	Primary reserve: available within 30 sec, released by TSO	Secondary reserve: available within 5 min, released by TSO	Minute reserve: available within 15 min, called by TSO from supplier	n.a.
Ireland	Primary operating reserve: available within 15 sec (inertial response/fast response)	Secondary operating reserve: operates over time frame of 15–90 sec	Tertiary response: from 90 sec onward (dynamic or static reserve)	n.a.
United States	Regulation horizon: 1 min to 1 h with 1- to 5-sec	Load-following horizons: 1 h within increments 5- to 10-min increments (intrahour) and several hours (interhour)		Unit-commitment horizon: 1 day to 1 wk with 1-h time increments

Source: Gul and Stenzel 2005.

Note: TSO = transmission system operator, n.a. = not applicable.

determined that the impacts of wind tend to increase with the time frame being studied. Because the variations of load and wind tend to be uncorrelated in short time scales (that is, wind generation is variable and wind production is not necessarily tied to increases in demand for electricity), most wind integration studies have found that only modest amounts of additional regulation are necessary with more wind. A rough rule of thumb is the additional regulation needed is equal to about 1 percent of the nameplate capacity of a 100 megawatts wind plant (NERC 2011). But other studies have found larger regulation impacts because units providing regulation cannot respond quickly enough to changes in net load and for errors in short-term wind forecasting (California ISO 2007; Hinkle and others 2010).

In Texas, ERCOT, which is the grid operator for most of the state, determines its regulation needs based on past or expected wind capacity. ERCOT examines the up and down regulation service, for every hour, that has been used in the past 30 days and for the same month the previous year, and applies a 98.8 percent deployment value. After that, ERCOT estimates the amount of wind capacity for the past 30 days and the same month of the past year. If the estimate of wind capacity in the last 30 days is higher than for the same month of the previous year, ERCOT will use the look-up factors in table 1.4 to determine how much additional regulation may be needed. For example, if 2,000 megawatts of additional wind was added in January 2011 as compared to January 2010, then 8.4 megawatts of additional regulation will be needed for the hour ending at 9:00 a.m. in January (4.2 megawatts*2).

Load Following

Load following includes periods ranging from 10 minutes to a few hours and includes spinning reserves (generators that are online and can respond quickly), nonspinning reserves (generators that are not online but can come online quickly), and supplemental reserves (generators that are not online but can come online over several hours and relieve spinning and nonspinning reserves). Wind integration studies have typically found a larger increase in the need for load following higher levels of wind generation, largely because of wind's diurnal output that in many cases may be opposite of the peak demand period for electricity. Wind output may fall off in the early morning hours when load is increasing, increasing the need for generating resources to ramp up to meet the rising electric demand. Conversely, wind power production may be higher during off-peak hours when load is decreasing or at minimum levels, increasing the need for generating resources that can ramp down. Therefore, adding wind generation will typically require more load-following resources to counteract the combined net variability of load and wind. Furthermore, with greater levels of wind, the distribution of hourly changes in load widens, with more frequent events of higher hourly changes in load, both positive and negative, resulting in a potential need for more ramping capability.

Table 1.4 Additional Up-Regulation per 1,000 MW of Incremental Wind Generation Capacity in ERCOT

Incremental megawatt adjustment to prior-year up-regulation 98.8 percentile deployment value, per 1,000 MW of incremental wind generation capacity, to account for wind capacity growth

Month	Hour ending																							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
January	2.8	4.2	3.1	3.7	2.5	0.4	2.3	2.2	4.2	5.9	7.6	5.7	4.7	3.3	2.8	2.3	4.0	8.6	4.2	2.7	1.6	2.7	1.4	1.6
February	3.6	4.0	2.9	2.9	1.5	1.8	5.2	3.5	4.9	6.0	5.1	5.2	5.3	4.2	4.3	3.5	3.8	8.6	5.5	1.9	1.4	3.1	1.9	2.2
March	5.5	5.3	4.6	4.2	2.6	3.3	7.1	7.9	6.8	5.7	4.2	3.4	2.8	2.6	2.7	2.3	2.9	7.7	6.8	2.1	1.1	3.0	1.5	2.8
April	3.1	3.6	5.0	4.0	2.4	2.5	8.5	11.6	10.0	5.6	4.2	3.4	3.2	2.5	2.1	2.1	3.5	9.2	8.2	4.1	1.0	0.8	0.0	1.4
May	3.6	3.3	4.3	4.3	4.2	3.3	8.7	8.8	8.1	5.7	6.0	4.4	3.6	3.8	3.9	4.2	4.7	11.6	5.9	0.6	0.0	1.0	1.4	2.5
June	2.3	2.6	3.3	3.7	3.9	2.4	8.5	8.2	6.6	4.5	4.2	3.1	2.5	2.5	0.7	0.2	1.3	7.5	3.3	1.7	0.7	0.3	0.6	1.3
July	1.0	2.8	4.4	3.7	3.0	3.2	11.2	10.2	6.5	5.3	3.3	2.2	1.4	0.4	-0.9	-1.3	0.3	3.4	0.9	1.1	0.1	0.0	1.0	1.2
August	1.4	3.8	4.5	4.5	2.2	0.9	6.3	6.8	6.6	6.6	3.2	2.6	2.1	1.2	1.4	1.3	1.3	4.6	1.2	0.9	0.7	0.8	1.1	1.3
September	3.2	4.0	3.7	3.5	1.8	1.9	6.9	7.7	8.3	6.9	3.5	4.8	3.8	2.3	1.6	1.2	3.0	9.2	3.1	0.9	0.1	0.4	0.8	1.9
October	3.4	2.8	2.4	2.2	1.7	1.8	5.0	5.8	6.1	5.9	4.0	5.4	3.2	2.2	1.2	1.7	3.1	6.8	0.8	2.1	0.0	0.2	1.8	2.5
November	2.7	3.2	3.6	3.0	2.2	2.3	4.6	5.3	6.9	6.8	5.1	5.6	4.1	3.7	1.8	1.7	5.8	12.8	4.8	3.8	1.0	1.6	2.2	1.4
December	2.8	2.4	1.4	2.1	1.2	0.4	2.8	2.7	3.8	4.6	6.8	7.0	6.0	4.4	3.3	3.0	5.0	9.9	4.3	2.6	2.1	4.3	2.0	1.5

Source: Ela, Milligan, and Kirby 2011.

Note: MW = megawatts.

Unit Commitment and Cost Impacts

Several wind integration studies have estimated the costs of integrating higher amounts of wind generation, defined as the increased system costs imposed by higher levels of wind generation. Two common methods include a flat block approach, where a power system with wind is compared to a system with an energy-equivalent flat block, and the cost difference is the integration cost. The second is the system cost that focuses on wind's impact on commitment and dispatch, and wind's net value from fuel savings and reduced wholesale prices. A newer, but still relatively untested, method is using an "ideal wind block" (perfectly forecasted) instead of a flat block (Milligan and others 2010a).

Unit commitment is the time scale with the largest wind integration cost impacts, up to almost US\$9.00 per megawatt-hour at wind capacity penetrations of up to 20 percent or 30 percent. The uncertainty of wind power production in the unit commitment time frame may result in higher variable costs through increased fuel consumption, and increased operating costs from ramping up generators and running them at less-than-optimal levels. The unit commitment cost impacts are contingent on the amount of and characteristics of dispatchable generation resources, the amount of the wind forecast error (and interactions with the load forecast error), the market and regulatory environment, and the characteristics of the wind generation resource as compared to load (DeCesaro and Porter 2009).

The costs to integrate wind power are nonzero to grid operators, and generally increase as the ratio of wind generation to conventional generation or peak load increases, with some reports suggesting that the rise is nonlinear as wind penetration increases (Zavadil and others 2009). So far, however, wind integration studies performed to date suggest that the projected costs to integrate wind are below US\$10 per megawatt-hour—and often below US\$5 per megawatt-hour—for wind power capacity penetrations up to about 40 percent of peak load (see figure 1.4).

The additional balancing reserves associated with higher wind power penetration is expected to be at most 18 percent of the nameplate capacity of wind power, and generally less, especially in studies that consider intrahour scheduling (see figure 1.5; Wiser and Bolinger 2011).

Separately, the International Energy Agency (IEA) found balancing costs range from \$1 per megawatt-hour to \$7 per megawatt-hour, at 20 percent wind penetration. It should be noted that these estimates do not include any opportunity costs for generation that may be needed to balance variability and are foreclosed from selling generation to the energy market, nor does it include any costs due to increased wear and tear for generators having to ramp up more frequently or operate at suboptimal operating levels (Chandler 2011).

Table 1.5 summarizes the different operational time frames and lists the resources utilized in those time frames. In addition box 1.3 briefly describes methodologies that can be used to determine short term reserve requirement due to wind and solar variability.

Figure 1.4 Integration Costs at Various Levels of Wind Power Capacity Penetration

Source: Wiser and Bolinger 2011.

a. Costs in \$ per megawatt-hour assuming 31 percent capacity factor.

b. Costs represent three-year average.

c. Highest over three-year evaluation period.

Special Challenging Events for Grid Operators **Integrating Variable Generation**

Besides the impacts to regulation, load-following, and unit commitment time frames described above, wind integration studies and practical experiences are finding that there are certain times of year and certain times of day that will be more challenging for grid operators to manage wind variability. Wind generation tends to be higher during off-peak times and lower during on-peak times, or put another way, wind generation is different (almost opposite) from load demand. This pattern will result in challenges to grid operators during two time periods: the morning load pick-up, when wind generation is typically ramping down while load is picking up, and during periods of low or minimum load, when wind production may be high. For the morning load pick-up, units that earlier may have been displaced when wind generation was online may not be able to adequately respond to increasing load when wind generation ramps down. That situation may require additional reserves from generation or from

Figure 1.5 Incremental Balancing Reserves at Various Levels of Wind Power Capacity Penetration

Source: Wiser and Bolinger 2011.
Note: MW = megawatts.
a. Includes some solar energy in addition to wind energy.
b. Three-year average.
c. Small, isolated island system.

Table 1.5 Operational Time Frames

Operating time frame	Available resources
Regulation	Generating units equipped with automatic generation control (AGC). Can be coal, gas, or hydro. Demand response can also provide regulation.
Load following	Spinning (online that can be called on within 10 min) or nonspinning (not online but can be called on within 30 min, typically). Usually gas or hydro, and coal in some systems. Demand response can also be used.
Unit commitment	Units that are relied upon by grid operators to meet expected demand on a day-ahead or multiday-ahead basis. All generating sources, and increasingly demand resources, are used.

Source: World Bank data.

Box 1.3**Estimating Short-Term Reserve Requirements from Wind and Solar Variability**

Different methods have been proposed by system operators and academics to provide sufficient reserves in the different time frames. These reserves are needed to make up for the differences between advance scheduled generation (of all types, including wind and solar) and actual production, and to protect the system against generation contingencies. To capture the expected variability and uncertainty of these renewable sources into the operating plans (regulation, load following, and unit commitment), different measures can be taken to grant a desired security benchmark, and these are listed as follows:

- The simpler set of measures that could be enforced consist in providing a deterministic amount of reserve to hedge against some generation failures, plus a term proportional to a desired number, " x ," of standard deviations of the expected forecast error of the net demand. This criterion ensures that no load will need to be disconnected in the event that a unit (or group of units) suddenly trips even if the forecast error of the net demand is x -times the standard deviation. While simple, this criterion neglects the probability of occurrence of such events, and simply protects against them at all times.
- Other measures explicitly recognize the need to include the probability of failing to meet the net demand (systemwide demand less wind/solar power production) in the provision of reserves. This probabilistic metric tells whether sufficient resources have been scheduled to ensure that the combined effect of system contingencies plus any difference between forecasted and actual net demand will not result in probabilities of disconnection higher than a predefined threshold. The merit of enforcing this approach is that the probability of failing to meet the demand is always bounded; however, it fails to account the extent of the potential deficits (for example, 0.1 or 10 megawatts with the same probability), and therefore the scheduling of the reserves might be economically inefficient if the cost of the reserve is higher than the cost of the possible disconnection.
- Other, more complete, set of measures use reliability metrics that account for both, the probability of failing to meet the net demand, and the extent of the potential deficit, all in terms of expected energy not served (EENS). The EENS is inversely proportional to the amount of reserve procured. These approaches usually penalize the EENS by the value of lost load (VOLL), which represents the average value that consumers place on the accidental loss of 1 megawatt-hour of electricity. By doing so, the reserve is procured up the point where it is justifiable in economic terms when compared to the benefits derived from it in terms of EENS cost reduction. Also, if the VOLL is high (systems demanding high reliability), the more expensive reserve would be easily justified as opposed to systems with low VOLL.

All these approaches are sensitive to the wind/solar forecasting error. That is, as the error increases (which is natural for longer forecasting horizons), all the approaches would naturally tend to provide larger amounts of reserve. Also if the forecasting tool used is

(box continues on next page)

**Box 1.3 Estimating Short-Term Reserve Requirements
from Wind and Solar Variability** *(continued)*

poor, these approaches would tend to cover the wider possible materializations of the net demand by setting larger amounts of reserve to be procured. The last two sets of approaches are also sensitive to the system reliability. That is, in systems in which its generation system undergoes contingencies less often, the amounts of reserve to be procured would be lower. These levels of reserve will still, however, be quite sensitive to the distribution of the forecasting error of the net demand, and as this increases, these approaches would respond by increasing the reserve. Finally, the last set of approaches is also sensitive to the value that customers place on the unserved energy, and as a consequence, the amount of reserve to be provided is balanced with its costs, tending toward a higher economic efficiency.

Source: World Bank data.

demand response. These type of reserves may be different to what operators have been used to, since they are not load-following reserves (given the magnitude of the variation), nor are they contingency reserves, given that the wind sources do not increase or dry up as fast as during a contingency event (when a generation goes from rated output to zero in second). Separately, high wind generation during light load periods can aggregate minimum generation problems (that is, too much generation for serving available electric demand, see box 1.4 for an example), while conventional units are already offline or operating at their lowest operating level without going offline. Grid operators will want to keep some nonwind-generating units online to meet the morning pick up in demand when wind production declines. Therefore, grid operators may need to curtail wind generation during extreme periods of minimum load, or determine whether they can encourage additional off-peak load during those times, or transmit the power off their system to other utilities or customers. Integration studies using production simulation models and multiple years of wind data will be able to project approximately when and for how many hours per year these challenging periods of morning increases in ramps and minimum loads will occur (DeCesaro and Porter 2009). The ability of the system to meet demand during low load conditions and high variable renewable output is becoming a more challenging situation than providing reserves for other types of situations where improved forecast can help.

Integration studies and operating practice may also lead to concluding that existing ancillary services need to be redefined, or to the identification of new ancillary services, such as a longer-duration nonspinning reserves to manage extreme wind events that could take place over several hours (Kirby and Porter 2007).

Figure 1.6 depicts a downward wind ramp in Spain, where wind output decreased by 75 percent over 6 hours, and an upward wind ramp that occurred

Figure 1.6 Example of Wind Ramps in Spain: Top Wind Power Drops, Bottom Combined Cycle Gas Power Output Increases

Source: Red Electrica of Spain (undated).

over 5 hours. This constitutes an event in the load-following and unit commitment time frame, which required large amounts of power output from units that could increase several hundred megawatts in output in 1 hour to reach to about 3,000 megawatts in about 5 hours.

Wind Integration Study Assumptions

Wind integration studies assume that the incremental wind being modeled and simulated is spread out geographically, leading to smoother and less-variable wind production, and that transmission and new generation is added as needed to maintain and preserve reliability. But if wind resources are concentrated in a geographic area, then the integration challenges will occur at lower penetrations, and mitigation strategies will need to be implemented sooner. One example is the Midwest Independent Transmission System Operator (Midwest ISO) in the

United States, where installed wind capacity is small compared to the Midwest ISO's total load and generation, but the concentration of wind in the Midwest ISO's western area (with more wind planned) is prompting the Midwest ISO to implement wind forecasting, to require wind to be part of the Midwest ISO's bidding and dispatch (instead of being taken as available), and to explore how to encourage more flexible generation. Another example in the United States is the Bonneville Power Administration (BPA), where most of the wind capacity is concentrated in the Columbia Gorge region of Oregon and Washington. BPA had to curtail wind power at times in the spring of 2011 because of high hydro and wind generation during periods of low electric demand (Wiser and Bolinger 2011). More examples of wind and solar integration are provided in the case studies on China, Germany, and Spain.

Overall, the variability of wind power generation adds to the variability on the grid in most time scales, and a key question that wind integration studies must address is whether there is enough existing capability on the grid to manage that increased variability, or whether new sources, such as new generation or increased levels of demand response, must be added to manage that variability. To date, no integration study has found a maximum technical limit of wind capacity that can be accommodated—the uncertainties are economic and operational, as in the amount of additional reserves a grid operator (and overseeing regulators and policy makers) wants to procure, whether greater ramping capability and flexibility can be extracted from existing generation or whether new generation (or curtailable demand) are needed, and what changes in operating procedures and what mitigation strategies may be necessary (Bai and others 2007).

While the operational experience indicates that low penetration levels will have limited impacts, the impacts could appear sooner depending on the system's existing inflexibility (for example, the lack of a well-developed transmission system, existing generation mix with slow responding units, poorly developed dispatch operation practices). Determining the impact at higher penetration levels (15–30 percent) or medium penetration levels (10–15 percent) in inflexible systems would require a proper integration study that can be performed with dispatch simulation models. Integration studies will be data intensive and must have high-resolution data (preferably minute by minute expected variation in output) on the expected output profiles of variable power sources. Appendix C of this book describes a basic approach that can be followed to perform such integration studies.

Other Findings from Operational Experiences

Several countries are already incorporating significant amounts of wind and solar generation. This chapter profiles three countries—China, Germany, and Spain—that have integrated large amounts of renewables (especially wind) in terms of installed capacity and have been able to manage the impacts to different degrees of success.

Box 1.4**Bonneville Power Administration's Environmental Redispatch Policy**

The Bonneville Power Administration (BPA) is a federal nonprofit agency in the Pacific Northwest region in the United States. The BPA markets wholesale electric power from 31 federally owned hydro plants, one nonfederal nuclear power plant, and several small nonfederal power plants. About 30 percent of the electric power consumed in the Pacific Northwest comes from the BPA. In addition, the BPA operates and maintains about 75 percent of the high-voltage transmission system in the Pacific Northwest (BPA 2010a).

In recent years, wind capacity has increased significantly in the BPA's service territory, with most of it being generated within the BPA's service territory but being exported and consumed outside of the BPA. Wind capacity in the BPA grew from 250 megawatts in 2005 to about 3,500 megawatts in 2011 and is expected to double again by 2014 (BPA 2010b). In spring 2011, high wind generation was combined with a large and sustained runoff from snowmelt that resulted in more hydropower than usual. As of June 2011, estimated streamflows on the Columbia River system were at roughly 136 percent or more of normal streamflows at numerous dams through the summer.

As a result, the BPA had far more generation than load for some hours in spring 2011. The BPA implemented what it called the environmental redispatch policy on an interim basis in May 2011. The policy—which includes a sunset date of March 30, 2012—entitles the BPA to curtail wind and thermal power generation, in lieu of spilling excess water over the dams. Spilling too much water over the dams would violate environmental laws, as too much spill would dissolve enough nitrogen in the river to potentially kill migrating salmon that are protected under the Endangered Species Act. Running the water through the hydropower turbines avoids this problem, but may produce excess power unless the other curtailment measures are taken. The BPA provides replacement power at \$0 per megawatt-hour, but will not sell it at negative prices. When curtailed, wind power generators lose production tax credits and renewable energy certificates valued at up to \$50 per megawatt-hour. The BPA maintains that it is unable to compensate wind power resources for this loss, as the cost would ultimately be paid by the ratepayers, which conflicts with the BPA's mandate to deliver low-cost power and repay its federal government debt. As of July 13, 2011, the BPA has curtailed about 97,557 megawatt-hour of wind power generation, or about 6.1 percent of the scheduled output of wind (Davidson 2011a).

The BPA's environmental redispatch policy has been controversial, and several wind power generators in June 2011 filed a complaint with the Federal Energy Regulatory Commission (FERC) against the BPA, alleging that its environmental redispatch policy is contrary to past the FERC orders and violates the wind generators' existing interconnection contracts and their associated firm transmission rights (Davidson 2011b). In early 2012 the FERC ruled that the BPA was not in compliance with open access transmission requirements and ordered the BPA to file new transmission tariff provisions, which the BPA did in April 2012. The FERC has not yet ruled on the BPA's filing.

Source: Various Sources.

China

China's electricity consumption has grown considerably since 2000, in connection with its rapid economic growth. From 1980 to 2009, annual electricity demand in China grew over 12-fold, from 295 to 3,660 terrawatt-hours (Kahrl and others 2011). Projections of future electricity demand by 2020 in China vary widely, ranging from 6,692 terrawatt-hours (Cheung 2011) to 11,245 terrawatt-hours (Kahrl and others 2011).

China occupies a unique place in integrating variable generation, having the most installed wind capacity in the world in an electricity system with limited trading and mostly inflexible generation. China has set a goal of generating 150 gigawatts of wind, 20 gigawatts of solar, 380 gigawatts of hydro, and 80 gigawatts of nuclear power by 2020. China also wants to get 15 percent of its energy consumption from renewable energy and nuclear power by 2020. China is also embarking on plans to develop seven 10 gigawatts wind power bases over the next decade. Assuming the country meets its 150 gigawatts target by 2020, wind power could provide 4 percent of China's electric generation (Yin, Ge, and Zhang 2011). Other sources suggest that as much as 220 gigawatts of wind capacity could be in place by 2020 (Qionghui and Xuehao 2011).

China has significant wind resources of 2,380 gigawatts of onshore wind potential and 200 gigawatts of offshore wind potential. Wind capacity in China grew from 300 megawatts in 2000 to about 42 gigawatts in 2010 (see figure 1.7). By energy contribution, wind provided 0.7 percent of China's electricity generation as of 2009 (Cheung 2011).

But not all wind capacity in China is interconnected, because of unavailable transmission or grid capacity. Of the wind capacity in place in China in 2010, 6.24 gigawatts was constructed but not commissioned, while another 4.45 gigawatts was under construction and not ready to be interconnected to

Figure 1.7 Installed Wind Capacity in China, 2000–10

Source: Cheung 2011.

the grid (Qionghui and Xuehao 2011). Wind curtailment is also significant in China, with wind capacity factors being lower as a result of wind curtailment and insufficient grid capacity. The capacity factor of wind was reported to be 23.7 percent in 2009 (Kahrl and others 2011).

Electricity Grid

The electricity grid in China is divided into several regional grids. The State Grid Corporation operates the Northeast, North Central, Central China, East China, and Northwest regions and encompasses 26 provinces in all.

Each grid is responsible for its own profit and loss, and there is little impetus for intergrid cooperation. Therefore, it is difficult for State Grid to be interested in building transmission to access wind in Western Inner Mongolia, or for the State Grid and South China grid to cooperate to access hydro in the south. But the grids are responsible for meeting China's renewable energy targets. Electricity dispatch in China is done using "equal shares" approach in which generators of a certain type are guaranteed a roughly equal number of operating hours to gain enough revenues to recover their fixed costs. The approach is economically and environmentally inefficient as low-efficiency generating units (high heat rates) may have the same number of operating hours as those units with low heat rates. China has experimented with environmental dispatch rules to prioritize renewables and clean coal generation.

China does not have a structured and transparent means of linking costs and retail electricity prices. Wholesale generation rates in China are roughly based on average costs. China uses a benchmark price that sets uniform prices for generators based on industrywide technologies and expected performance, as well as estimates of annual output and fixed and variable costs. Because of benchmark pricing, generation supply curves are typically quite flat in China.

More than 80 percent of the electricity trading between regions and provinces are handled under long-term contracts, where the quantity and prices of electricity traded are annually agreed to based on demand and supply forecasts. Electricity trading, therefore, is quite rigid, with the tradable amount capped and prices fixed while demand and the export capacity of a province can change over time (Cheung 2011).

Impact of Wind Power on the Grid

Wind production is typically nearly opposite that of load (that is, wind is high when load is low and vice versa), and that has been the case in China as well. The China Electric Power Research Institute designed and implemented a day-ahead wind forecasting system in Jilin; mean square root errors for the day-ahead forecast ranged from 11.05 percent to 19.08 percent (Yin, Ge, and Zhang 2011). Wind forecasting has since been implemented in 12 regional and provincial power companies in the north and northeastern grids of China, covering about 15 gigawatts of wind capacity. China recently has required all wind generators to provide a wind forecast by July 2012.

Figure 1.8 An Example of Daily Load, Net Load, and Wind Production in China

Source: Qionghui and Xuehao 2011 (unspecified region of China).

Figure 1.8 shows a daily pattern of wind, load, and net load from an unspecified day. Wind production nearly matches load in the early morning hours before dropping off while load increases.

Further adding to the complexity of integrating variable energy generation in China is that energy resources are concentrated in regions far from the electric demand centers. Two-thirds of the wind and solar resources are located in north and northwest China, and 80 percent of the country's hydro resources are in southern China, but the majority of electric demand is located in eastern and central China.

The State Grid developed the National Wind Power Research and Inspection Center in December 2010 (Qionghui and Xuehao 2011). China is also in the midst of implementing a grid code for wind that requires wind turbines to meet low-voltage ride-through standards. Finally, China is building transmission to interconnect more wind capacity to load centers, including for the seven 10 gigawatts wind bases. By the end of 2010, China had expended over 41.8 billion RMB (renminbi) for transmission for wind projects. One ultrahigh AC voltage transmission line and one ultrahigh DC voltage transmission line are now operating in China, and more are scheduled to be constructed over the next 10 years to interconnect the wind power bases (Yin, Ge, and Zhang 2011). Table 1.6 provides a high-level overview of wind integration in China.

Germany

Germany has a long history of policy support for renewable energy development and, as of the end of 2010, had 27.2 gigawatts of wind capacity (German Federal Ministry for the Environment 2011). Peak demand in Germany is approximately 80 gigawatts, while minimum demand can be

Table 1.6 Synopsis of Case Study of Wind Integration in China

<i>Integration issue</i>	<i>Synopsis</i>
Ancillary services	Most ancillary services provided by a few plants, with money collected from all coal plants and paid to the plants providing the ancillary services. Ancillary service impacts of wind under study
Integration issues	Need for timely expansion of transmission grid to interconnect wind power Balancing generating and load mostly done at the provincial level Electricity dispatch performed under an “equal shares” approach where generators are guaranteed a roughly equal number of operating hours to ensure enough revenues to cover fixed costs Significant wind curtailment in some regions because of high levels of wind capacity and the amount of less flexible CHP (combined heat and power) units that provide heat in the winter
Integration strategies	In the process of implementing technical standards (grid code) for wind as well as verification procedures Rolling out wind forecasting to help improve short-term dispatch operations at the local and regional levels Implementing new procedures to timely planning and building of transmission

Source: World Bank data.

as low as 30 gigawatts, leading to high levels of wind penetration during off-peak nighttime hours. The main mode of support has been a feed-in tariff (FIT) that offers guaranteed payments for renewable energy output.

Due to the strong growth in wind power in northern Germany, Transpower (as E.ON Netz) was one of the first grid operators in the world to develop grid codes specific to wind. These codes have been revised several times and adopted by other German transmission system operators (TSOs). The grid codes require wind generators to withstand and ride through voltage drops of up to 15 percent for 625 milliseconds, and to provide grid support and reactive power for up to 3 seconds (Porter 2007). All wind facilities (and other generators) are required to have approved switchgear and reactive power exchange, keep operating during system disturbances, and keep voltage and frequency within a specific range. Older wind facilities used to be exempt from these requirements. Recently, however, Germany has instituted a repowering program, where these older wind turbines are being replaced and wind facilities need to conduct retrofits to meet the voltage drop and ride-through requirements. Germany also instituted voltage ride-through requirements for solar PVs.

Germany operates as a single-price-area energy market, which includes a day-ahead, an intraday, and reserve markets. All wind energy in Germany must be sold on the spot market known as the Energy Exchange (EEX) and settles every 15 minutes. TSOs pay wind energy suppliers the FIT price and put the wind energy on the EEX.

In compliance with the German law, each of the TSOs is obligated to take all electricity generated from renewable energy sources within their control area and compensate the generators for their electricity at the established FIT rate.

Impact of Wind Power

High wind output can lead to loop flows from north to south and east to west within Germany, and with countries such as Poland, Austria, Belgium, and the Czech Republic. France and the Netherlands have installed phase-shifting transformers to prevent loop flows through their systems. Available transmission capacity at the borders between Germany and other countries are adjusted daily based on advance forecasts of wind power. Transmission congestion is handled through redispatch of power plants to manage overloads, and if necessary, plant curtailments, including wind. Generators that are redispatched because of high wind production are paid for lost revenues including start-up and shut-down costs (Ernst and others 2010).

Planning and Forecasting

In 2005 the German Energy Agency (dena) released the first *Planning of the Grid Integration of Wind Energy in Germany Onshore and Offshore up to the Year 2020* (dena Grid Study I). The study examined scenarios for the increased use of renewable energy sources for the years 2007, 2010, 2015, and 2020. The dena Grid Study I identified current and projected inadequacies in the power system and compiled a list of needed electric grid upgrades that will be required by 2015 to uphold Germany's projected renewable energy development.

The dena Grid Study II examined transmission options using traditional technologies (Basic) along with new technologies including: high temperature resistant aluminum conductors (TAL); flexible line temperature management systems (FLM); high-voltage DC lines (HVDC); a combination of the three (hybrid); and a universal use of underground lines (GIL) (see figure 1.9).

Figure 1.9 dena Grid Study II Transmission Scenarios

Identified grid expansion and annual costs for the investigated variants

Source: dena Project Group 2010.

Note: FLM = flexible line temperature management system, GIL = underground lines, HVDC = high-voltage DC lines, TAL = temperature-resistant aluminum conductors, km = kilometers.

Other planning initiatives include expanding the use of electricity storage, including a dena program for using the natural gas grid. Excess electricity would be used to produce hydrogen, which can then be fed into the natural gas network or processed into synthetic gas and stored for later use.

The German TSOs utilize several forecasting services at the same time and use a weighted sum of these forecasts adjusted to observed weather patterns. For example, Amprion uses 10 different wind forecasts, which are entered into a “combination tool,” which then produces an optimal forecast taking into account the weather situation.

Due to the implementation of these aggregate forecasting methods, the day-ahead wind power production forecast root mean square error for Germany as a whole averages about 4.5 percent (European Wind Energy Association 2010). TSOs sell the day-ahead forecasted amount into the day-ahead spot market; they also sell the difference between the day-ahead and intraday forecast into the intraday spot market. Any remaining deviations are covered by balancing reserves. Table 1.7 provides a synopsis of wind integration in Germany.

Spain

Spain has a peak demand of about 45 gigawatts and an off-peak demand ranging between 19 and 25 gigawatts. Wind energy penetration has been as high as 54 percent, occurring in August 2009 (López 2010). Nearly all of the electricity consumed in Spain is generated domestically, with less than 1 percent imported from outside the country.

Generation from solar PVs has increased in Spain from 40 gigawatts-hour in 2005 to 5,347 gigawatts-hour in 2009. Only 2 percent of solar PVs are connected to the transmission grid in Spain; the remaining are connected to the distribution grid and cannot be observed by the Red Eléctrica de España (REE).

Nearly all of the solar PVs in Spain are connected to the distribution grid, while 70 percent of the CSP in Spain is connected to the transmission grid. Lack of grid operator awareness of solar PVs is considered a problem, as the PV plants

Table 1.7 Synopsis of Wind Integration in Germany

<i>Integration issue</i>	<i>Synopsis</i>
Ancillary services	Variable generation imbalances shared by the four transmission system operators (TSOs). Secondary reserve system has reduced need for all reserves except for regulation, which has remained the same.
Integration issues	Loop flows on high wind production days significant. Net transmission capacity available on interties between Germany and other countries determined in part by wind forecast
Integration strategies	TSOs use ensemble forecasting and have a 4.5 percent root square mean error rate for country as a whole. Grid codes put in place for wind in 2005 and recently extended to solar Procedures to manage unscheduled and loop flow within the country and with neighboring countries

Source: World Bank data.

are not required to send REE real-time production and operation information. Spain currently only has real-time measurement data of about 150 megawatts of PV. For now, Spain uses meteorological predictions to estimate how much solar PV exists each hour. Spain has real-time information on all CSP plants.

Currently, the variability of solar PV production does not exceed that of load and is not considered to be an issue for secondary regulation. The geographic diversity of solar has also helped, as solar PV plants have been installed nearly everywhere in Spain except for the northernmost provinces.

For wind, REE has identified the following challenges with integrating higher levels of wind generation:

- *Wind production is not correlated with electricity demand.* Wind generation may occur at different times than when electricity is needed, particularly in the summer. According to REE, the maximum contribution of wind to winter peak demand is about 4 percent, and 1.5 percent in the summer.
- *Wind generation will trip if wind speeds exceed 25 meters per second.* Spain adopted a grid code that requires wind turbines to ride through faults shorter than 100 meters and to survive voltage drops lower than 85 percent per unit. About 85 percent of wind capacity in Spain can meet the fault ride-through requirements.
- *The variability of wind generation can be problematic.* REE states that wind upward and downward ramps can be 1,500 megawatts per hour, but wind forecasts help mitigate this issue to some degree.

Over 70 percent of Spain's wind capacity is connected to REE's transmission network, allowing REE to monitor wind production. REE uses a central wind forecast for all wind generation. The wind forecast provides hourly wind forecasts for the next 10 days, and a forecast by transmission system node that is updated every 15 minutes for the next 48 hours. Confidence intervals at 15 percent, 50 percent, and 85 percent are provided, with the 85 percent level used to determine if there are enough units committed.

Planning and Forecasting

Spain coordinates forecasting and scheduling of solar plants, and although the early indications suggest that solar forecast accuracy is not very good past 6 hours, the forecast error is tolerable because of the coincidence of solar resources with peak demand.

Wind developers seeking to sell their output on the wholesale market in Spain must arrange for interconnection to the transmission system. Spain requires wind projects over 10 megawatts to be associated with a control center to communicate directly with REE. REE can control wind generation by sending orders from its control system to the wind generator's control center. Wind companies are required to use their best forecast, to offer all their production, to update intraday schedules according to revised wind

forecasts, and to pay for any balancing energy needed to offset deviations from the schedule (López 2010).

REE reports that both up and down reserves may be insufficient in certain hours due to outages of conventional generation, demand prediction errors, wind or solar forecast errors, wind units tripping because of high wind, or not enough flexible generation. If up reserves are insufficient, REE may commit additional thermal units through real-time dispatch. If there are insufficient down reserves, then REE may decommit thermal units in real time. If down reserves are still insufficient, REE curtails nonmanageable renewable generation as a last resort (López 2010). The short-term reserve-related impacts have been more observable in the tertiary regulation and deviation management ancillary services. For instance, tertiary down-regulation grew from 2,107 gigawatts-hour in 2007 to 2,983 gigawatts-hour in 2010. Deviation management in the up or down mode also more than doubled from about 1,000 gigawatts-hour average to 2,300 gigawatts-hour average (see appendix A for more details). Note that in megawatt terms the doubling represents no more than 300 megawatts of conventional power generation.

Until January 2009, Spain provided bonus payments or penalties for reactive power as determined by the actual power factor and the time of day. The payment was a percentage of the market and premium price and varied from –4 percent for a power factor of less than 0.95 at peak and flat rate periods to an 8 percent bonus for a power factor of less than 0.95 inductive in valley periods or less than 0.95 capacitive in peak rate periods.

In October 2006 Spain adopted a grid code that required wind turbines to stay operating if voltage dropped to 20 percent of nominal voltage lasting up to 500 milliseconds, followed by a ramp up to 80 percent of nominal voltage in another 500 milliseconds and a more gradual recovery to 95 percent of nominal voltage 15 seconds from the occurrence of the grid fault (Fernández 2006). About 85 percent of the wind capacity in Spain is certified as compliant with Spain's grid code.

All generators, including wind and solar, are responsible for the costs of any schedule deviations and for paying for the costs of the balancing energy necessary. A penalty is applied if the individual plant schedule deviations are opposite to grid needs. Therefore, if a generator generates less than is scheduled, it pays the market price for balancing generation if the deviation supports the grid or the maximum “up reserve” price if the deviation is not in support of the grid. If a generator generates more than is scheduled, it pays the balancing cost for a generator not to produce and is paid the market price if the extra generation is in support of the grid, and the minimum price if not (López 2010).

Synopsis of Wind

Table 1.8 provides a synopsis of wind and solar integration in Spain.

More details for the three country case studies can be found in appendix B.

Table 1.8 Synopsis of Wind Integration in Spain

<i>Integration issue</i>	<i>Synopsis</i>
Ancillary services	Have seen small impacts in some reserves, particularly for short-term reserves to account for wind forecast errors
Integrations issues	Weak interconnections to surrounding countries Use of wind curtailment has increased because of transmission congestion, insufficient reserves, or maintenance of system stability
Integration strategies	Uses ensemble forecasting. Mean absolute error is about 10 percent for day-ahead forecasts. Dedicated control center installed for renewable energy technologies Flexible generation (gas) to respond to special wind ramp events Grid codes in place for wind; Spain is considering extending them to solar

Source: World Bank data.

Solar Integration

Defining Solar Technologies

Broadly, two types of solar technologies are being deployed commercially: concentrating solar power (CSP) and photovoltaics (PVs). An important characteristic of all solar technologies is their diurnal and seasonal pattern (that is, peak output typically occurs in the middle of the day and in the summer), meaning that solar is well matched with summer peak demand. Solar generation may also compliment wind generation in that solar power may be produced during hours when wind generation is low or not available (NERC 2009; figure 1.10). A wind and solar integration study done for the California Energy Commission illustrates this point by comparing average load, average net load (average load minus wind minus solar), average wind output, and average solar output for one day (Bai and others 2007). Aggregate solar and wind production can match up with average net load (NERC 2009).

Experience to Date with Solar Integration

There is less experience with solar integration, and less study of solar integration, than with wind to date (Brinkman and others 2011). Reasons include that solar development is more recent than wind, and solar projects have often (but not always) been deployed in small, distributed units that are hard to monitor collectively, or may not be visible to grid operators. In addition, solar output without storage is more correlated with peak demand and does not generate at night, meaning the problems with morning load pick-up and minimum load that were previously discussed are not as relevant with solar (Chandler 2011). CSP plants with storage can release stored energy at night, meaning its output is predictable from solar production in the day and from stored energy at night (Chandler 2011). The output of multimewatt PV plants in the southwestern United States has, however, varied by over 70 percent in 5–10 minutes on partly cloudy days (NERC 2009).

Other reasons for the lack of solar integration studies is a lack of high-quality solar data, particularly subhourly, which makes it difficult to estimate

Figure 1.10 Average Load, Net Load, and Wind and Solar Hourly Profiles from a Grid Integration Study in California

Source: Bai and others 2007.

Note: MW = megawatts.

solar integration impacts or whether solar needs additional reserves. Wide-area solar data are available with low-time resolution, or subhourly solar data are available but with limited geographic coverage. Satellite data are available covering a wider geographic area but data are available only hourly. There are high-resolution PV data and solar measurements available from individual sites, but there are few collections with multiple time-synchronized PV or solar insolation sites. To do a solar integration study, researchers will need solar data ranging from seconds to hours for large solar plants, dispersed PV plants on distribution feeders, and aggregate data on the estimated amount of solar plants that system operators must integrate (Brinkman and others 2011).

That said, solar without storage offers grid integration challenges, and some of these challenges are outlined below.

Solar systems without storage and PV produce electricity in both diffuse and direct sunlight. The rising and setting of the sun contributes to 10–13 percent variations in PV output over 15 minutes for single-axis tracking PV plants. The time for a cloud to shade the entire PV system is contingent on the PV system size, cloud speed, and cloud height. Clouds can result in large variations at a single point. Changes in solar insolation at a single point can be over 60 percent of the peak insolation in seconds. For a PV plant of 100 megawatts, the time the plant will be shaded will be in minutes, not seconds. Changes in PV production

from clouds are not uniform. Clouds may affect one part of a plant before another, or affect only one part of the plant and not the other. Similar changes can occur in PV systems located in deserts from sand or dust storms. One example is a 10 megawatts PV plant in Abu Dhabi, which has seen 40 percent decreases in production from sandstorms (Todorova 2009).

Diversity within a PV plant can occur, but is limited over longer-time scales. Diversity can occur within PV plants, and the amount of smoothing of PV production depends on the size of the plant, with smoothing occurring more for larger PV plants than smaller PV plants. In addition, for multimegawatt PV plants, ramps for single solar insolation meters can be more severe than multimegawatt plants in time scales of up to about 10 minutes. But for time scales longer than 10 minutes, changes in output will be similar between a single solar insolation meter and a multimegawatt PV plant.

Diversity is more pronounced among multiple PV plants. Several studies indicate significant smoothing in PV output among multiple PV plants. Analysis of several time-synchronized solar insolation measurements in the Great Plains (six PV plants in Las Vegas, four PV plants in Arizona, and two PV plants in Colorado) suggests smoothing occurs on longer time scales between separate PV plants than within each PV plant. Specifically, for the six PV plants in Las Vegas, aggregating the plants smoothed the 1- and 10-minute ramps, with the 60-minute ramps smoothed as well, but not as much as the 1- and 10-minute ramps (see figure 1.11).

Figure 1.11 One- and 10-Minute Ramps from Six PV Plants in Las Vegas

Source: Mills and others 2009.

For the four PV plants in Arizona, the 10-minute ramps were reduced by 50 percent through aggregation of any pair of sites. Such reductions can be expected if output between the plants is not correlated (see figure 1.12).

For the two plants in Colorado, there was a smaller reduction in 10-minute ramps, suggesting there was more correlation between the two plants, and that the smoothing benefit of aggregation may be different by region. These results have given rise to a general rule of thumb that if ramps over a certain time are uncorrelated between all N plants, then aggregate variability is expected to scale with $1/\text{square root of } N$ (Mills and others 2009).

A review of these data and the academic literature suggests that at individual PV sites, PV is more variable than wind intrahour (subhourly), and the changes in output for PV between 5 and 15 minutes are more significant than for wind. But the distance needed between PV sites to gain the smoothing of subhourly output appears less for PV than wind (Mills and Wiser 2010).

Some early research on the potential additional reserve costs from adding solar power found that the costs are comparable with that of wind, if geographic

Figure 1.12 Cumulative Distributions of Ramps from Individual PV Plants, Pairs of Various Spaced Plants, and the Aggregate of All Plants in Arizona

Source: Mills and others 2009.

Note: km = Kilometers. Figure 1.12 depicts the cumulative distributions of changes in power output in 10 minutes (between 98.8% and 100%) of individual PV plants (Gilbert and OPV1), of a pair of PV plants (Glendale and UPG), all four PV plants (All4) and four separate lines representing the aggregate of output of pairs of PV plants, located 12.5 km to 50 km apart. All of the PV plants are located in Arizona and are based on one year of 10-minute data from individual, single-axis tracking PV systems. Figure 1.12 indicates that aggregating pairs of individual PV plants can result in a 50% reduction of the most severe ramps.

Table 1.9 Estimated Unit Cost of Reserves to Manage Short-Term Solar Variability

Time scale	Increased reserve costs (\$/MWh)				
	Reserves constant throughout year			Reserves change with position of sun	
	Solar		Wind	Solar	
	1 Site (\$)	5 Sites (\$)	25-Site grid (\$)		
1-min deltas	16.7	4.8	1.2	0.9	0.8
10-min deltas	17.3	4.4	1.0	0.2	0.7
60-min deltas	5.0	1.6	0.6	0.5	0.5
Total cost	39.0	10.8	2.7	1.6	1.9

Source: Mills and Wiser 2010.

Note: MWh = megawatt-hour.

diversity for solar is accounted for. Table 1.9 estimates the potential reserve costs for 1, 5, and 25 solar sites, and for a wind project. The reserve costs for a single solar site are substantial, but the costs decline significantly as more solar sites are incorporated and the geographic diversity impacts are incorporated.

Lack of Visibility of Distributed Generation

One emerging issue for grid operators is that solar and wind generation connected at the distribution level is not visible to grid operators and can have impacts if the solar and wind generation is large enough. Although this issue is commonly associated with solar because of the amount of distributed solar being developed, it is also associated with wind, particularly in Europe where many wind installations are small projects that are interconnected with the distribution grid. In Germany, thousands of megawatts of individual and small clusters of wind turbines are connected to the distribution system. Each wind turbine is operated autonomously, and grid operators suggest that bulk-system load-forecast performance has deteriorated in Germany because distributed generation could not be measured or planned for. Hawaii Electric Co. also has reported similar visibility problems with distributed PV systems. Real-time communications with distributed generation units may be necessary for power systems with high levels of distributed generation.

Separately, the IEEE-1547¹ standard for distributed generation requires that distributed generation units disconnect from the grid if a voltage disturbance occurs. But as the penetration of distributed generation such as wind and solar increases, the IEEE-1547 standard may result in the significant loss of generation. The reconciliation between IEEE-1547 and grid codes for utility-scale generation will need to occur and are the subject of a North American Electric Reliability Working Group in the United States (NERC 2009). Germany has taken the step of adopting voltage ride-through standards for PV systems, and it is under consideration in Spain and in other countries (López 2010; Mills and others 2009).

Note

1. The Institute of Electrical and Electronic Engineers (IEEE) produces many standards that are accepted worldwide.

Integration Strategies and Solutions

As described in previous sections, the multitude of integration studies and experience gained to date with integrating wind and, increasingly, solar generation, is giving rise to a number of acknowledged strategies and solutions for integrating variable generation. These strategies and solutions are discussed in more detail below and are also summarized in table 2.1.

Table 2.1 Strategies for Integrating Variable Generation

<i>Strategy</i>	<i>Description</i>
Forecasting	Essential once variable generation is beyond small penetration; will help with minimizing fuel and operational costs of balancing plants and help maintain reliability
Subhourly markets	Will help access flexibility from existing generating units and reduce the need for ancillary services
Shorter scheduling intervals	Submitting schedules closer to real time will allow for more accurate forecasts of wind and solar generation but may lead to higher costs from the increased starting and stopping of conventional power plants.
Consolidating balancing areas	Larger balancing areas improve both load diversity and the diversity of wind and solar generation, reducing overall variability. Larger balancing areas can also access a deeper stack of generation to help balance the variability of load and generation resources.
Flexible resources	Higher amounts of variable generation will result in the need for flexible generation, that is, for generation to increase or decrease operations more quickly and a wider operating range.
Displacement of existing generation	Higher levels of variable generation may reduce short-term market prices and can result in reduced revenues for conventional generation. That, in turn, may cause some conventional units to retire that may be needed for maintaining reliability.
Grid codes	The impact of grid codes will be more evident at larger penetrations of variable generation to ensure that variable generation stays online during voltage changes or can ride through system faults. But grid codes need be adapted early in the process of scaling up renewables to ensure that as the share of these resources grow, it does not affect grid reliability as a whole.
Demand response and demand side management	Demand response could shift load to correspond to periods with high wind production, helping to minimize or avoid curtailment of wind generation and help manage conditions of high wind generation at times of low or minimum load.

(table continues on next page)

Table 2.1 Strategies for Integrating Variable Generation (*continued*)

<i>Strategy</i>	<i>Description</i>
Changing unit commitment practices	Greater amounts of variable energy generation increase uncertainty, particularly in the day-ahead time frame. Some of this increased demand for flexibility can be mitigated with changes to unit commitment practices by adding intraday unit commitment or by making unit commitment more probabilistic based on expectations of wind and solar forecast errors.
Transmission to access wind and solar resources	New transmission will be instrumental in successfully integrating more wind and solar generation, and is particularly important as wind and solar power projects are constrained to areas with adequate wind and solar resources.
Wind curtailment	Past wind integration studies in the United States have stated that at higher levels of wind penetration, wind generation may need to be curtailed for a small number of hours per year, such as during periods of low demand and high wind production to decrease the rate of upward ramping. Wind curtailment is occurring presently in some regions and countries, in large part because of transmission constraints.
Advances in wind technology	Wind projects have significantly advanced in technical capabilities in recent years and can provide reactive power, voltage control, Automatic Generation Control (AGC), and increase or decrease power in response to system frequency events.

Source: World Bank data.

Forecasting

When utility-scale wind projects first started coming online in the United States in the 1980s and 1990s, a common practice was to simply take the wind generation on an as-available basis and back off other generation that had been committed to incorporate the wind generation. Such practices are acceptable for wind generation that accounts for a small percentage of the utility load, as the variability of wind generation is swamped by load variability and can be easily absorbed. Such practices become untenable at higher levels of wind penetration, as it imposes operational inefficiencies (more generation has to be held back as reserves to meet the increased uncertainty and variability of wind generation) and increased fuel consumption from more starts and stops of conventional generation. These factors become significant as wind penetration increases. A General Electric (GE) study assessing the potential grid impacts of 10 percent wind penetration determined that the variable operating cost savings increase from \$335 million to \$430 million when state-of-the-art wind forecasting is used, with another \$25 million in benefits when perfect wind forecasting is used (Piwko and others 2005). The Intermittency Analysis Project conducted by GE for the California Energy Commission demonstrated a benefit of \$4.37 per megawatt-hour with state-of-the-art wind forecasting and another \$0.95 per megawatt-hour for perfect wind forecasting (Bai and others 2007). As a result, the North American Electric Reliability Corporation (NERC) considers wind forecasting to be essential if higher levels of wind generation are to be successfully integrated in the United States (NERC 2009).

There are several types of wind forecasts that can be deployed. Persistence forecasts simply predict that the amount of wind generation that is occurring presently will occur in the next time interval, usually either subhourly or for a

period of up to 6 hours. Hour-ahead wind forecasts apply updates to generate forecasts as frequently as 5 minutes for the next 4–6 hours ahead. Day-ahead wind power forecasts provide hourly forecasts for the next 2–4 days and are typically updated every 6–12 hours. More specialized wind forecasts for ramps and severe weather forecasts are now emerging and being implemented. Ramp forecasts function more as an “alert” system to warn grid operators of the likelihood of wind ramps from increasing wind production as a storm passes over, then a drop-off in wind production from the storm moving on or from wind turbines shutting down from high wind speeds. Ramps are more of a probabilistic-type forecast, as severe weather and ramp forecasts are nonlinear events. Forecasting techniques designed to keep the mean average error low fare poorly in forecasting ramps.

Wind forecasts can predict the overall shape of wind production most of the time, and more advanced techniques are under development. Large deviations can occur in level and timing from extreme events that are difficult to forecast. Such deviations can lead to large wind forecast errors. The steepness of the power curve for wind turbines can also lead to forecast errors, as power output increases from 10 percent to 90 percent in the wind speed interval between 6 and 12 meters per second. Another source of wind forecast error is from wind turbines shutting down operation in storm events, where the turbine stops and power drops to zero. These events can be difficult to predict and contribute to large wind forecast errors, as wind forecasts are designed to minimize mean or root mean square error. But that underestimates large weather changes that can lead to wind ramps. Increasingly, separate forecasts are being prepared on the probability of wind ramps. ERCOT has implemented a ramp forecasting tool.

Wind forecasts use numerical weather prediction (NWP) models as input that predict wind speed, wind direction, and other meteorological estimates, such as turbulence factors, typically in hourly resolution for several days. Day-ahead forecasts use only NWP data and have a forecast range of 6 hours to days. For shorter forecast periods of up to 8 hours, online measurement data (wind production and wind measurements) is combined with NWP data. How often NWP data are updated affects wind forecast accuracy. Older data increase the wind forecast horizon and the forecast error. NWP data are updated one to four times per day. If only updated once per day, then it can be almost 24 hours for the next forecast update. NWP data are also computationally time intensive and can take several hours to compute. If data are 24 hours old, NWP calculations take 6 hours, and wind power production is forecasted 8 hours ahead, then forecasts may be based on data that are 38 hours old, which can negatively affect wind forecast accuracy. Short-term forecasts have two update cycles—one for the online measurement data and one for the NWP data. Online measurements can be updated continuously and are given more weight in shorter time horizons.

The accuracy of wind forecasts depend on the site, time of year, the quality of data on individual wind turbine availability and outages, and weather conditions.

A representative mean average error for a one-hour-ahead forecast for a single wind power plant varies from 4 percent to 12 percent of wind plant capacity.¹ The mean absolute error for day-ahead wind power forecasts for a single wind plant varies from 12 percent to 25 percent of nameplate wind capacity. These values can be reduced by as much as 50 percent if wind plants are aggregated over a broad geographic region (NERC 2010b).

There is increasing interest in using ensemble forecasts (use of multiple wind forecasting providers, or multiple wind forecasts from a single forecasting provider), where the best wind forecast for specific conditions can be selected, or a combination of forecasts can be utilized based on a time or forecast period. Therefore, the final wind forecast could be the “single best forecast” or a weighting of individual forecasts. A best practice with using ensemble forecasts is to ensure they capture the major source(s) of uncertainty. This will vary from region to region, and from season to season. The ensemble forecasts can either be deterministic (a weighted average of the wind forecasts in the ensemble) or probabilistic with uncertainty limits, or both (NERC 2010b). Another best practice is to conduct a cost-benefit study to determine if the additional value justifies the higher costs. The California Independent System Operator (ISO) found the additional costs did not justify using ensemble forecasts, but the answer may be different for other grid operators (Blatchford and de Mello 2009).

Forecasting for solar is necessary as well. The short-term variability of a single photovoltaic (PV) plant can be high, although, as noted, there are diversity benefits with multiple PV plants. The ease of forecasting solar depends on the amount of solar radiation that reaches the surface and can be measured. That, in turn, depends on clouds (that is, the depth of clouds, or the concentration of water or ice in clouds), the amount of water vapor, and the quantity of aerosols. Hour-ahead solar PV forecasts rely on statistical models, using time series of on-site insolation measurements, off-site measurements of clouds and solar insolation, and satellite images of water vapor channels that might interfere with solar radiation. The day-ahead solar PV forecasts use physics-based models, with forecasts of transmission as the major variable. Solar power forecasting is comparable to wind power forecasting, but once the sun has risen, clouds are the main factor on the variability of solar power generation and the uncertainty of solar power forecasts. In the short term, some clouds are fairly stable and move with winds at the level of the clouds. For longer time scales, clouds can change shape, increase their size, or break apart. Numerical weather prediction models will be required to simulate cloud changes.

Multiple methods will be required to forecast solar output at various time scales. Presently, short-term solar forecasts are based on cloud observations and movements. Sky imagers near solar plants can help locate approaching clouds and estimate the impact clouds will have on estimated solar power production. In addition, satellite images can help indicate the direction and speed of

approaching clouds. For longer time periods, numerical weather prediction models will be needed, such as estimating solar insolation for multiple days (NERC 2010b).

It appears, though, that solar forecasts will tend to be more predictable than wind, as good solar sites have low cloudiness, and the forecast errors for solar are small if clouds are not a major factor. In contrast, good wind sites have high wind speeds, which lead to high variability. In addition, satellites provide frequent, high-resolution cloud data, which help short-term solar forecasts (Mills and Wiser 2010). There is no such tool available for short-term wind forecasting, although the U.S. Department of Energy and the National Oceanic Atmospheric Administration issued a request for proposals (RFP) in 2011, and selected two companies to formulate such a forecast (NOAA 2011).

Note

1. The mean absolute error (MAE) is the absolute value of the error divided by a predicted or reference value. Another measurement of the wind forecast error is the root mean squared error (RMSE), which involves obtaining the total square error first, dividing it by the total number of individual errors, and then finally taking the square root. The RMSE is more sensitive than the MAE to outliers, giving a high weight to large errors since they are squared prior to being averaged.

Contribution of Variable Power Sources to Supply Adequacy

Previous chapters have dealt with the operational impacts of variable power sources such as wind and solar power. These impacts refer only to the operations time frame, which might vary from a few seconds to several minutes or hours. In the operational time frame, the impacts that need be managed (as described by the operational experience and desktop studies reviews) are mostly constrained to the need to compensate fast wind variations within the different dispatch time frames so that demand is met without the need for considerable amounts of new operating reserves. As described in the previous chapters, system flexibility is key to containing the operational impacts and costs of managing increased amounts of renewables, when operational impacts and associated costs start becoming more noticeable.

In the previous chapter we explained the difference between operating reserves and long-term planning reserves. Long-term planning reserves are required to ensure the system will be able to meet the demand. The ability of a system to meet current and future demand is usually referred to as supply adequacy. Sometimes terms are used interchangeably and supply adequacy is also referred to by some as supply security. In this chapter we will use the term supply adequacy.¹

Definitions and Metrics for Supply Adequacy

The ability of a system to meet current and future demand is largely determined by the expected demand and the ability of existing and future sources to meet such demand. Adequacy will depend as well on the ability of the system components to be there when needed. All components in a system are subject to potential failure and such potential failures have direct impacts on the adequacy of the system. In addition, the type of supply has a great deal of impact on system adequacy. For instance, systems that depend on a large amount of hydropower have traditionally understood that water is not always available in the same amounts in the different seasons of the year. In addition, extreme dry years could lead to lower

supply and that to reduced system adequacy. The way in which other variable renewable power sources such as wind and hydropower help with supply adequacy requires understanding of how supply adequacy is measured. We briefly discuss some of the basic definitions and then use them to summarize the impact of wind and solar power on long-term (or planning) system adequacy.

One of the basic measures to determine the adequacy of a grid to meet demand is the **reserve margin**. The reserve margin is usually defined as the difference, in percentage terms, between the peak demand and the peak supply available at the time of peak demand.

$$\text{Reserve Margin} = (\text{Peak Supply} - \text{Peak Demand}) / \text{Peak Demand}$$

For instance, if a system has a peak demand of 1,000 megawatts and the peak generation available at peak demand is 1,200 megawatts, the reserve margin is 20 percent (see figure 3.1).

The reserve margin is a deterministic measure that cannot capture the uncertainty of a certain event that can impact the ability of the system to meet demand. For instance, if out of the 1,200 megawatts available, if there is a high probability that 200 megawatts can fail at the same time, then a reserve margin of 20 percent would be too optimistic, given that there is a large likelihood that the reserve margin can fall to 0 percent given the high probability of failure of 200 megawatts. Given that all type of generation plants can inevitably fail, probabilistic measures have been adopted for many years to measure the adequacy of a system. Two of the most basic probabilistic measures of supply adequacy are the Loss of Load Probability (LOLP) and Loss of Load Expectation (LOLE).

The *Loss of Load Probability (LOLP)*, as the name indicates, measures the probability that the system will not be able to meet demand. No system will

Figure 3.1 Representation of Traditional Reserve Margin

Source: World Bank data.

have 0 percent loss of load probability, but low levels are certainly possible. The LOLP is usually computed using convolution models that determine all possible states of the system and their probability. Any state of the system (n) where supply is not enough to meet demand will contribute toward the LOLP. For example, if out of ten possible states in the system, two (one the amount of generation under outage or failure) cannot meet demand, then the LOLP is the sum of the probabilities (p_i) that these two scenarios happen.

$$\text{LOLP} = \sum_{i=1}^n p_i, (\text{Peak Load} > \text{Available Supply})$$

The LOLP is a measure that does not easily transmit how good or bad the adequacy of a system could be. For instance, a LOLP of 0.04 seems low, but it is not easy to understand if it is much better than 0.02. An alternative measure of system adequacy that tries to solve this problem is the Loss of Load Expectation (LOLE), which measures the ability of a system to meet demand by determining the number of days in a given year when supply will not meet demand. This metric is more amenable and provides a great sense of adequacy of a system. For instance, a LOLE of 1 day clearly transmits the sense that the system may not be able to meet demand only during 1 day in a year. It is easier to understand what a LOLE of $\frac{1}{2}$ day or 5 days can mean to a given system. The first clearly is a greater level of adequacy—5 days in a year where demand may not be met clearly points out to a more acute adequacy problem than $\frac{1}{2}$ day.

Besides the probabilities that equipment will fail, determining the LOLE requires understanding the demand profile of a system. The LOLE is determined by multiplying the probability of a state of the system by the number of hours when the demand is expected to be above the available supply in such a demand state.

$$\text{LOLE} = \sum_{i=1}^n p_i, \text{time}(\text{Peak Load} > \text{Available Supply})$$

As an example, consider the yearly duration curve shown in figure 3.2. The load duration curve (LDC) represents a system demand whose peak is about 280 megawatts and whose minimum demand is about 50 megawatts. The LDC shows that demand will be above 150 megawatts 25 percent of the time during a year. If under all predicable scenarios for supply in the system only 150 megawatts of supply can be guaranteed, this means that approximately 25 percent of the time of the year the demand will not be met. In a year this means a large $\text{LOLE} = 0.25 \times 365 = 91$ days.

Contribution of Variable Renewables to Supply Adequacy

The simplest way to estimate the contribution of variable sources to supply adequacy is to follow a similar estimation as the one used for hydropower production. Hydropower production is usually determined based on forecasts based on historical data of water inflows, which are used to produce synthetic series of

Figure 3.2 Load and Load Duration Curve to Estimate the Loss of Load Expectation

Source: World Bank data.
Note: MW = megawatts.

power output. For sources such as wind and solar power a similar approach can be followed. Assuming data have been gathered and used to produce long-term forecasts of wind speed or solar radiation, using power plant characteristics, a synthetic series of power output for wind and solar power can also be produced. For a given year, the total expected output, given expected wind speed divided by the technical maximum output of the power plan, is defined as the plant factor. For instance, if a 200 megawatts wind power plant is expected to produce

on average only 40 megawatts through the year, then the production factor is said to be $40/200 = 20$ percent. This does not means that at any given point of time the wind power plant will be producing 40 megawatts—it could happen that the plant is producing 0 megawatts at one time when the wind speed is not enough to turn the blades (for example, at midday) and the full 200 megawatts at other times during top wind speeds (for example, at nights).

The plant factor of variable power sources is the simplest, most straightforward estimate of their contribution to supply adequacy. This means that in the previous example the 200 megawatts wind power plant will not contribute 200 megawatts to system adequacy, but only approximately 40 megawatts. Following our previous example, it would mean that adding the 200 megawatts wind power plant to the system with 1,200 megawatts installed capacity and 1,000 megawatts peak demand will increase the reserve margin only from 20 percent to 24 percent, see figure 3.3.

Using the expected plant factor of variable power sources is straightforward and gives planners and policy makers a rough idea of the contribution of variable power sources to supply adequacy in the system. The approach could be easily integrated into least-cost planning models to ensure the system as a whole can meet desired reliability margins. This approximation is, however, highly limited since it does not consider key variability characteristics of wind or solar power and how these could interact with peak demand and, therefore, with the supply adequacy of the system. For instance, wind power tends to peak at night times

Figure 3.3 Plant Factor to Approximate Contribution of Wind Power to Reserve Margin

Source: World Bank data.

Note: In the example a 200 MW wind power plant is added to a system with 1,200 MW of fully available installed capacity. Since the average plant factor of the wind plant is only 0.2 percent, its contribution to peak supply is estimated at 20 MW. This increases available capacity from 1,200 to 1,240 MW, which takes the reserve margin from 20 percent to 24 percent. This is a small contribution considering that adding a 200 MW plant of fully available supply would increase the reserve margin from 20 percent to 40 percent.

when winds are strong. For a thermal system whose peak demand happens in the afternoon, when the power output of wind may be close to zero, the load factor may be an overoptimistic approximation of the contribution of wind power to supply adequacy. For a system whose peak demand correlates more with wind or solar power output, the contribution of these sources to supply adequacy would be higher.

A Probabilistic Approach to Estimate the Contribution of Variable Renewables to Supply Adequacy

Probabilistic measures of supply adequacy are more adequate to capture the potential interactions between demand, other supply options, and the variable renewable power sources and their impacts on supply adequacy. Since the LOLE is widely known to the industry it is convenient to use such a metric to determine the contribution of variable power sources to supply adequacy. The approach consists basically of considering wind or solar power sources as an energy resource. The expected energy output of the renewable sources is reduced from the expected demand and the LOLE is determined for the residual demand. The contribution of wind or solar power sources is determined by gradually increasing the demand until the same LOLE is achieved if compared with the demand without subtracting the output from the variable power sources. The additional demand that the system can handle, while maintaining the same LOLE, is equivalent to the contribution of the variable power sources to supply adequacy. This approach and variations of it are increasingly being utilized by grid operators to assess system adequacy with large amounts of variable power sources.

As an example, consider the load and Load Duration Curve (LDC) whose maximum demand is 280 megawatts (see table 3.1). For this particular example, we assume that the supply is mainly from three conventional power plants for a total of 350 megawatts of installed capacity.

The forced outage rate (FOR) indicates the probabilities that the generation unit will go out of service. With these characteristics, table 3.2 lists all possible states of the generation system and computes the LOLE of 9.35 days per year, which is a system with considerable supply adequacy problems (note that the traditional reserve margin for this system would be $350 - 280/280 = 25$ percent).

Table 3.1 Example: Three Power Plants and their Forced Outage Rates

<i>Unit</i>	<i>MW</i>	<i>FOR</i>
1	50	0.02
2	100	0.03
3	200	0.05
Total	350	

Source: World Bank data.

Note: MW = Megawatts; FOR = Forced outage rate.

Table 3.2 Example: LOLE Only with Conventional Power Supply

State	Total	U1	U2	U3	COPT		Total	%	LOLEi
	capacity out	0.02	0.03	0.05	Calculation	Prob	capacity in	Time L>C	Probi
1	0	1	1	1	$= 0.98 \times 0.97 \times 0.95$	0.903070	350	0	0
2	50	0	1	1	$= 0.02 \times 0.97 \times 0.95$	0.018430	300	0	0
3	100	1	0	1	$= 0.98 \times 0.03 \times 0.95$	0.027930	250	7.465924	0.208523
4	200	1	1	0	$= 0.98 \times 0.97 \times 0.05$	0.047530	150	45.40954	2.158316
5	150	0	0	1	$= 0.02 \times 0.03 \times 0.95$	0.000570	200	24.0408	0.013703
6	250	0	1	0	$= 0.02 \times 0.97 \times 0.05$	0.000970	100	75.52709	0.073261
7	300	1	0	0	$= 0.98 \times 0.03 \times 0.05$	0.001470	50	100	0.147
8	350	0	0	0	$= 0.02 \times 0.03 \times 0.05$	0.000030	0	100	0.003
Total						1.000000			
LOLE (%)									2.603803
LOLE (d/y)									9.373692

Source: World Bank data.

Note: COPT = capacity outage probability table; LOLE = loss of load expectation, Prob = probability.

Two different cases are considered to determine the contribution of variable power sources to supply adequacy. In the first case it is assumed that a 100 megawatts wind power plant is added, in the second a solar power plant of 100 megawatts. The assumed outputs of these power plants is described in figure 3.4. The figure shows demand curves after subtracting expected wind and solar power output. The original LDC and the resulting LDCs, with wind and with solar power, are also presented in figure 3.4.

As can be noticed in the residual demand functions, solar power in the example is more coincident with peak demand, which has a direct impact on the residual demand to be met. On the contrary, wind power output (as happens frequently) is exhibiting a larger power output during low demand periods, resulting in little reduction of peak demand. The contribution of both solar and wind power output to supply adequacy can be determined, as described in the previous section, by computing the LOLE of the resulting LDC. As shown in table 3.3, the LOLE reduces from 9.37 to 8.15 days if the wind power plant is added. On the other hand, if the solar power plant is added, the LOLE reduces from 9.37 to 3.87 days (see table 3.4).

Using the procedure in box 3.1 and by adjusting peak demand of the residual demand until the original LOLE is achieved, it can be concluded that in this example the 100 megawatts power plant contributes to supply adequacy as if it were only a 25 megawatts power plant of fully available capacity (firm power). Given the coincidence of solar power in this example to peak demand, the contribution of a 100 megawatts power plant to system adequacy is equivalent to that of 88 megawatts of firm power.

The actual contribution of any of the sources in a given system will depend on the expected power profile outputs, their variability, and how such characteristics combine with system demand profiles and the availability of other

Figure 3.4 Example: Wind and Solar Output, Residual Demands with Wind and with Solar Power, and Equivalent Lead Duration Curves

Source: World Bank data.

Table 3.3 Example: Contribution of a 100 MW Wind Power Plant to Supply Adequacy (LOLE Reduces from 9.37 to 8.15 Days/Year, Equivalent to 25 MW of Firm Capacity)

State	Total capacity out	U1 0.02	U2 0.03	U3 0.05	COPT		Total capacity in	%	LOLEi
					Calculation	Prob			
1	0	1	1	1	$= 0.98 \times 0.97 \times 0.95$	0.903070	350	0	0
2	50	0	1	1	$= 0.02 \times 0.97 \times 0.95$	0.018430	300	0	0
3	100	1	0	1	$= 0.98 \times 0.03 \times 0.95$	0.027930	250	13.14316	0.367089
4	200	1	1	0	$= 0.98 \times 0.97 \times 0.05$	0.047530	150	35.85739	1.704302
5	150	0	0	1	$= 0.02 \times 0.03 \times 0.95$	0.000570	200	23.0654	0.013147
6	250	0	1	0	$= 0.02 \times 0.97 \times 0.05$	0.000970	100	53.88668	0.05227
7	300	1	0	0	$= 0.98 \times 0.03 \times 0.05$	0.001470	50	84.70796	0.124521
8	350	0	0	0	$= 0.02 \times 0.03 \times 0.05$	0.000030	0	100	0.003
Total						1.000000			
LOLE (%)									2.264328
LOLE (d/y)									8.151581

Source: World Bank data.

Note: COPT = capacity outage probability table; LOLE = loss of load expectation.

Table 3.4 Example: Contribution of a 100 MW Solar Power Plant to Supply Adequacy (LOLE Reduces from 9.37 to 3.87 Days/Year, Equivalent to 88 MW of Firm Capacity)

State	Total capacity out	U1 0.02	U2 0.03	U3 0.05	COPT		Total capacity in	%	LOLEi
					Calculation	Prob			
1	0	1	1	1	$= 0.98 \times 0.97 \times 0.95$	0.903070	350	0	0
2	50	0	1	1	$= 0.02 \times 0.97 \times 0.95$	0.018430	300	0	0
3	100	1	0	1	$= 0.98 \times 0.03 \times 0.95$	0.027930	250	0	0
4	200	1	1	0	$= 0.98 \times 0.97 \times 0.05$	0.047530	150	18.43318	0.876129
5	150	0	0	1	$= 0.02 \times 0.03 \times 0.95$	0.000570	200	3.667671	0.002091
6	250	0	1	0	$= 0.02 \times 0.97 \times 0.05$	0.000970	100	49.58257	0.048095
7	300	1	0	0	$= 0.98 \times 0.03 \times 0.05$	0.001470	50	100	0.147
8	350	0	0	0	$= 0.02 \times 0.03 \times 0.05$	0.000030	0	100	0.003
Total						1.000000			
LOLE (%)									1.076315
LOLE (d/y)									3.874733

Source: World Bank data.

Note: COPT = capacity outage probability table; LOLE = loss of load expectation; Prob = probability.

conventional and nonconventional sources in the system. Diversity of variable power sources will usually increase their contribution to supply adequacy; if resources have similar profile power outputs and these profiles do not greatly coincide with critical demand periods, their contribution to supply adequacy will be reduced. For example, if wind power output is highest at night in a given system and the wind is a little diversified, it may happen that even if the

Box 3.1**A Probabilistic Approach to Measuring the Contribution of Variable Renewables to Supply Adequacy: Determining Renewables “Firm” Contribution**

- Step 1. Determine Loss of Load Expectation (LOLE_o) considering the system Load Duration Curve (LDC_o) demand without the contribution from renewable sources
- Step 2. Forecast renewable production and reduce such production from the System Load Curve to obtain the Residual load duration Curve (LDC_n)
- Step 3. Determine the LOLE of the system to meet the residual demand
- Step 4. Increase demand across all hours of the Residual LDC until the LOLE is the same with and without the renewables supply LOLE_n = LOLE_o
- Step 5. The capacity (“firm”) contribution of the renewable source is

$$\text{Firm Contribution of Renewables} = D_n - D_o$$

$$D_n \text{ is peak demand corresponding to LOLE}_o$$

$$D_o \text{ is peak demand corresponding to LOLE}_n$$

Source: Keane and others 2010.

Note: Based on a LOLE approach to resources adequacy of variable power sources from the IEEE Task Force on Capacity Value of Wind Power.

wind capacity is increased its contribution to supply adequacy will not increase given that its contribution to the peak is limited. In a situation such as this, wind power contribution to supply adequacy will in fact reduce in percentage terms as wind power capacity is added to the system. This situation has already been identified in actual supply adequacy assessment of systems with high shares of renewables and in various supply adequacy assessments cited in the next section.

Contribution of Variable Renewables to Supply Adequacy and Evidence from International Experience

International experience indicates that variable power sources, such as wind and solar power, are mainly energy sources whose contribution to supply adequacy is limited, if compared to that of conventional power generation sources. If variable power sources are not diversified, and do not coincide with critical demand periods, their contribution to supply adequacy can be further reduced. It is always possible to combine large amounts of different variable power sources and achieve the desired level of reliability. In such a situation, the cost and implementation time will most likely be the true limitation to the amounts of renewables that a system should and can integrate in a given period of time.

While variable power sources are often cost-competitive in certain conditions as an energy source, this does not mean they will be equally cost-competitive to solve supply adequacy problems. This is especially true when the adequacy problem in a given system is related to meeting peak demand with sources whose availability at that time is reduced or uncertain. For instance, this would be the case for meeting afternoon peak demand in a system where wind power outputs can dry out at such time of the day. In such circumstances, meeting the peak demand would require overinstalling wind power plants to ensure that their combined output is such that peak demand can be met within a certain probability. While the cost of energy over the life of a wind power plant could be comparable to other sources, meeting the peak could have completely different costs (see box 3.2).

The contribution of variable renewable power sources to system supply adequacy has recently been assessed in different countries. These assessments are rapidly becoming a standard practice in systems with a large amount of renewables. Such assessments are not only important to understand the actual contribution of variable renewables to supply adequacy and to plan accordingly for a system that meets required standards, but are also sometimes required to remunerate renewables for their contribution to “firm” capacity. Remunerating variable renewables for their contribution to system capacity, and not just their energy supply, is a common practice in systems that do not have feed-in tariffs (FITs).

For instance, while the share of wind power in energy supply is expected to continue increasing in Ireland, its contribution to supply adequacy is expected to diminish. The total installed capacity of wind power in 2008 is about 1,067 megawatts, peak demand is 5,086 megawatts, and the capacity of conventional (dispatchable) power sources was 6,213 megawatts. Other variable renewable energy sources had an installed capacity of 185 megawatts. In accordance with its duty to assess the adequacy of the system to meet expected demand, EIRGRID, the transmission system operator for Ireland, prepared the Adequacy Report for the Period 2009–15 (EIRGRID 2008). The share of wind energy to energy demand has greatly increased from 1.6 percent in 2002 to 7.1 percent in 2007. As can be seen from a traditional reserve margin perspective, the system would be able to meet its peak demand without wind power. In fact, in 2008, EIRGRID reported that the contribution of wind power to the peak demand (that happens during winter in the evenings of a weekday) was zero.

Going forward, the capacity of installed wind power generation is expected to increase, since it is mandated to meet the government goal of supplying 40 percent energy from renewables by 2020. But the contribution of wind power to system adequacy, which is assessed using the LOLE methodology, is expected to continue decreasing, following recent trends. The capacity contribution of wind power has fallen from 34 percent in 2002 to 23 percent in 2007, and is expected to go down further to just above 10 percent in terms of total installed capacity by 2015 (see figure 3.5).

Box 3.2**Renewable Technologies Can Provide “Base-Load” Power or “Peak-Power,” but at Higher Costs if Compared with Other Conventional Technologies Traditionally Used for These Purposes at Current Costs**

Base-load power is a term used to describe generation from power plants whose economic characteristics are such that it is convenient to operate them at constant full output during the lifetime of the plant to meet a large portion of the demand below which total consumption never falls, leading to low-cost electricity supply. Base-load units tend to have high capital costs and low operational costs. They could be hydro, nuclear, or coal power depending on the resources available to a system. Base-load units tend to be large in their relative size to other units in the system and do not usually participate in regulation or load following, but provide other services such as system inertia, which are important to maintain reliability during electrical faults in the system. Base-load power is therefore mostly a description of the economic characteristics of a set of resources in the system. Variable renewable power sources whose availability is not guaranteed 24/7 can provide base-load power if a large enough combination of diversified plants is added to the system to guarantee a constant output. The same can be said about meeting “peak power.” This can be achieved if a large enough combination of wind, solar, and hydropower plants, whose complementarities could combine, produce a flat output or the required peak power. But such “base-load” power or “peak-power” may not be cost competitive at current costs if compared to other base-load and peak-power options. The cost will likely be higher given that an over installation of higher capital cost options such as wind and solar will be required to meet the same energy requirement.

While the levelized energy of some renewables, such as wind power, could be competitive if compared to conventional power sources even without considering externalities, guaranteeing the same energy requirement can lead to largely different costs. For instance, a 100 megawatts wind power plant with good wind resources can lead to a levelized cost of electricity of \$9 ¢ per kilowatt-hour, which can be comparable to a levelized cost of a 100 megawatts gas turbine that is also at \$9 ¢ per kilowatt-hour (second graph below). But assuming a system needs to meet a peak demand of 100 megawatts, meeting such demand will require an over installation of wind power assuming that wind output is largely noncoincident with peak demand (as often happens). Assuming a 100 megawatts wind power plant can guarantee only 20 megawatts at peak, then 500 megawatts of installed wind power will be required to meet the peak demand. Considering the capital and operational costs of these technologies as presented in the figure below, the cost to meet peak demand with wind power will be about \$93 ¢ per kilowatt-hour, which is various orders of magnitude higher than that of the gas turbines whose cost to meet peak demand is very close to its levelized cost of electricity.

(box continues on next page)

Box 3.2 Renewable Technologies Can Provide “Base-Load” Power or “Peak-Power,” but at Higher Costs if Compared with Other Conventional Technologies Traditionally Used for These Purposes at Current Costs *(continued)*

Source: Created using globally available cost of these technologies. Externalities not included.

Note: Left axis—capital and operational cost of wind and single-cycle gas turbine. Right axis—levelized cost of electricity and cost to meet a yearly peak of 100 megawatts. The competitiveness of variable power resources depends on a large number of factors, especially on their production patterns and how they combine with other renewable power sources through the transmission system and how they correlate with demand. For instance, solar power can be highly coincident with peak demand and so its competitiveness to meet the peak can radically increase. Combining resources is also key to reducing costs. This could be done by combining solar with and without storage, wind, hydropower, and demand management. Hydro, solar power and new wind technologies could also be combined to provide other system services required to maintain reliability, such as system inertia requirements. Renewables can technically meet large amounts of the energy needs in a system. It is not that variable renewables are technically limited to provide certain types of supply such as base or peak power. The limitations may be the cost (and affordability implications) and the time and technical capacity required to adapt system operations and planning to a new environment.

Source: World Bank data.

The decreasing contribution of wind power to system adequacy is due to its mismatch (noncoincidence) with peak demand and the lower quality of new wind sites to be developed. Wind power in the island also tends to behave homogenously, without diversity, and therefore its contribution to adequacy is impacted further negatively.

In Spain while the production of all sources is in a special regime (of which wind power holds the highest share, reaching 35 percent of total demand in 2010), the contribution to peak demand of wind power and other sources in the special regime was constrained to about 22 percent of the peak demand or about 10 gigawatts of instantaneous output out of the 32 gigawatts of installed capacity. In 2010 the peak demand was 44 gigawatts while the total installed capacity was 99 gigawatts, out of which 20 gigawatts corresponded to wind power and about 4 gigawatts to solar photovoltaic (PV) and concentrating solar power (CSP). Combined cycle plans with an installed capacity of 23 gigawatts

Figure 3.5 Expected Evolution of the Contribution of Wind Power to Supply Adequacy in Ireland

Source: EIRGRID 2008.

Note: MW = megawatts.

are still the largest contributor meeting peak demand, which in 2010 reached 17 gigawatts at peak demand. This confirms that wind and other renewables do have a role to play in system adequacy, but such adequacy is still principally insured by conventional power sources.

Various assessments worldwide consistently report the downward trend of wind power to contribute to system adequacy as the penetration of wind increases in the system. This is due to the fact that an increase in installed power capacity with actual output not coincident with peak demand will not necessarily increase its contribution to system adequacy or firm output. The IEA Task 25 on Design and Operation of Power Systems with Large Amounts of Wind Power has reviewed the capacity contribution of wind power reported in various studies. These results are reproduced in figure 3.6. As can be seen at low penetrations of wind their contribution to capacity can be as high as 40 percent for some regions of the United States where wind power output largely coincides with peak demand. In other countries such as Germany, the reported contribution is less than 10 percent for a penetration of 20 percent and declined to about 5 percent for penetration levels close to 50 percent.

Factors that impact the contribution of variable power sources include coincidence with peak demand, the diversity and complementarity between resources, and how these interact with the other supply options in the system. Determining the contribution of variable power sources, or any other for that matter, requires an actual adequacy evaluation for the particular system using methods such as the LOLE approach described in this paper. A system whose

Figure 3.6 Contribution of Wind Power to Adequacy Decreases as Penetration Level Increases

Source: Holttinen and others 2009.
Note: GW = gigawatt.

adequacy is already high may benefit less from the addition of variable power sources since energy supplies may have limited impacts on improving adequacy. If system adequacy is low in a way that energy (and not only capacity) is already scarce in the system, addition of variable power sources could directly contribute to supply adequacy as presented in the examples in this chapter, but the cost of such adequacy improvements could become the principal concern in such circumstances.

Note

1. Supply security can be used to refer to other attributes of supply, such as those not highly depending on external sources. In addition, security is a term that in the power system operations jargon is more widely used to refer to the ability of the system to meet demand faults in the system such as power line outages or others.

Summary

The total worldwide installed capacity of wind and solar projects is growing rapidly, and several countries are noticing increasing penetrations of wind and solar in their electricity generation mix. In addition to operating experience being gained from adding wind and solar capacity, several grid integration studies (focusing mostly on wind but increasingly on wind and solar) have been performed assessing potential grid and operating impacts from adding higher amounts of wind and solar capacity. The methodologies and levels of detail for these grid integration studies differ, as do the characteristics of the power systems being studied, but several common findings have emerged from these studies. The findings reveal that costs to integrate wind and solar generation are below \$10 per megawatt-hour, and often below \$5 per megawatt-hour, for capacity penetrations of wind of up to 40 percent. These studies have also found that certain time periods, namely the morning increase in peak demand when wind output decreases and minimum load hours when the load is down and wind production is higher, can be difficult for grid operators to manage and these periods need to be focused on. These studies also have found that certain factors, such as the geographic diversity of planned or operating wind and solar projects, the composition of the existing generation fleet and how flexible or inflexible it is to start and stop quickly, the size of the balancing area (with larger balancing areas making it easier to integrate variable generation), and the availability of transmission both within a region or country and to external regions or countries, will indicate the ease or difficulty a country or region will have in integrating wind and solar generation.

Perhaps just as important, the electric power industry and those that conduct research on grid integration have not found a maximum level of variable generation that can be reliably incorporated, and it is clear that it is as much an economic question (how much cost in additional reserves or grid impacts is acceptable) as a technical question. Furthermore, the electric power industry and grid integration researchers are focusing on better understanding the impacts of wind and solar generation in the short term (subhourly and hourly) and on day-ahead reliability planning and generation dispatch.

Operating practice with variable generation and results from the grid integration studies have also resulted in several solutions and strategies that should be pursued in integrating large amounts of wind and solar generation, as described below:

- *Conduct a grid integration study that addresses the right issues for the foreseen level of variable generation integration and current system conditions.* Conducting such a study before significant amounts of wind and solar capacity is added can help determine the potential system impacts of variable generation, inventory the capability of existing generation to operate more flexibly, estimate whether additional transmission may be needed, and find and evaluate “difficult” operating periods, such as high-load/low-wind and solar periods or low-load/high-wind periods. As explained earlier, various approximation methods can be applied if there are inadequate data or resources to perform a full-fledged grid integration study, although they will not be as comprehensive or provide the detailed analysis that grid integration studies provide.
- *Implement wind and solar forecasting.* Wind and solar generation can be reliably incorporated without forecasting at very low levels of penetration by energy, but if these levels increase, then day-ahead and short-term forecasting will become necessary for grid operators to anticipate how much wind and solar generation can be expected. If incorporated in generation dispatch, wind and solar forecasts can save money through reduced fuel and operation costs. An increasing trend is for forecasts to include potential up and down ramps from the passage of storm fronts.
- *Create larger balancing areas when possible.* Larger balancing areas help smooth the variability of wind and solar resources by drawing from a larger geographic area. In addition, larger balancing areas allow access to more generating resources for providing reserves, and allow for greater load diversity as well.
- *Create more flexible electricity schedules and markets.* Allowing subhourly scheduling will help access generation that can provide reserves that would not be provided if held to longer schedules, such as hourly. In addition, having more flexible schedules improves the accuracy of scheduling variable generation, as short-term forecasts tend to be more accurate.
- *Encourage more flexible generation.* Adding variable generation increases the need for generation resource flexibility, that is, for generation to move up and down in response to changing net load as opposed to base-load resources that have long start-up and shut-down times. Such flexibility can be added through new generation or from accessing flexibility from existing generation resources. But generators are reluctant to operate more flexibly, as that imposes additional costs through equipment wear and tear, and increased fuel consumption, with little or no compensation. Attracting flexible generation may need to be done through resource planning, contracts, or through incentives to operate flexibly.

- *Implement grid codes.* Unless designed to withstand grid faults or voltage reductions, wind and solar plants may trip offline, possibly leading to reliability concerns if the amount of lost wind and solar capacity is significant enough. Several countries have implemented grid codes that require wind projects to ride through grid faults, and some are being updated for wind projects to provide reactive power or frequency control, or to limit positive ramp rates. Grid codes are also being considered for solar power to withstand grid faults and lower voltages, and for distributed solar projects to be visible to grid operators.
- *Utilize the more grid-friendly features of newer wind turbines.* Advances in wind turbine designs are continuing to be made, and newer wind turbines can provide frequency response and system inertia as needed
- *Build new transmission to access wind and solar resources.* New transmission will be a necessary step toward successfully integrating more wind in many regions and countries, to interconnect wind and solar generation and to access areas with electricity demand, as variable generation tends to be located away from areas with higher electric demand.
- *Access demand response and demand side management.* Greater use of demand response and demand side management can help with providing additional reserves as needed and for balancing the variability of wind and solar generation. Most demand response and demand side management programs have not been designed with variable generation in mind, although initiatives in Denmark and in the Pacific Northwest are under way in response to higher levels of variable generation.
- *Revise unit commitment practices.* Revising present unit commitment practices to occur more often and incorporating a probabilistic approach could result in using shorter-term wind forecasts that are generally more accurate and result in the committing of fewer reserves.
- *Implement wind curtailment.* Maximum wind production can be several times larger than average wind production, meaning that at 20 percent wind penetration by energy, wind production may equal consumer demand for some hours. Several grid integration studies have found that wind curtailment may be necessary during difficult operating periods (such as high wind and minimum load) and has increased in parts of the United States and in China, Spain, and other countries.

Each of these possible options should be viewed as a menu; picking a strategy or set of strategies requires a full assessment to determine the lowest-cost options. For example, it would not be desirable to install storage systems to solve a variability problem whose magnitude can be solved simply by improving forecast and changing dispatch functions. As the amount of renewables increases, the lowest-cost options to improve flexibility should be exhausted. A system can sooner reach the point where more-expensive options are needed

if compared to another system. For instance, if forecasting has already been implemented, and further diversity of resources to smooth out variability cannot be achieved with transmission (for example, due to a small geographical area), flexibility may require investing in other options such as fast generation options or storage to directly address the variability impacts.

Clearly identifying potential operation problems will require proper network integration studies and implementing the solutions will also require gaining some technical capacity and institutional and regulatory rearrangements whose nature and magnitude will largely depend on the status of infrastructure, operational practices, and expected levels of variable renewables in the particular system. Table 4.1 provides a summary of the potential preconditions in these areas that could arise in the context of many systems in the early stages of integrating renewables.

Table 4.1 Strategies to Manage Variability in Grid Operations and Some Prerequisites for Their Application and Effectiveness

<i>Strategy</i>	<i>Prerequisites: technical, institutional, or regulatory</i>
Forecasting	As with demand forecast, it needs to be used to influence dispatch operations at different time frames: day ahead, hours ahead, and tens of minutes ahead. It is critical to define the responsibility of renewable generation providers to provide forecasting or key data necessary to grid operators and dispatch centers to prepare or improve forecasting based on data or forecasts already provided by renewable energy suppliers. These responsibilities can be clearly defined as part of the operational rules usually inscribed as part of the grid code.
Subhourly markets	These can also be implemented on vertically integrated systems, where short-term dispatch is not necessarily used to price spot energy transactions. It is effective at managing the impacts of variability as long as forecasting is influencing dispatch. In systems where short-term dispatch serves the function of price determination for energy exchange, subhourly markets have traditionally been established, and their design and definition requires a wider consultative process with all stakeholders. Market rules regarding intraday price determination and billing may also need to be adjusted accordingly.
Shorter scheduling intervals	These require better information and telecommunication systems in and well-structured process for linking short-term operations with real-time dispatch in the Supervisory Control and Data Acquisition (SCADA) and Energy Management Systems (EMS) systems. There should be a discipline in maintaining short-term operations and real-time schedules.
Consolidating balancing areas	Consolidated balancing areas are effective to the extent variability in the different areas is complementary with other areas. This tends to happen only in systems where geographical areas are large and span across varied climatological and topological conditions that impact renewable resource availability. Hence, systems in small territories or islands may not benefit largely from this strategy.

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Table 4.1 Strategies to Manage Variability in Grid Operations and Some Prerequisites for Their Application and Effectiveness *(continued)*

<i>Strategy</i>	<i>Prerequisites: technical, institutional, or regulatory</i>
Flexible resources	If a system is already endowed with adequate operating and planning resources and these resources have the capability to respond quickly to wind or solar events, there should be incentives or regulated approaches to make sure these resources become available when needed. If a system is already dedicatory in reserves, conventional power sources will mostly only add energy to the system even at high penetration levels. In such cases and at high penetration levels of renewables, adding fast-responding units may require carefully planned and deliberated action.
Grid codes	Grid codes are as good as their enforcement. It is critical that grid codes are actually enforced and appropriate tests are carried out strategically to ensure old and new technologies comply with the required performance standards.
Demand response and demand side management	Demand response depends on many factors such as the type of consumers being targeted and the types of instruments being used (price incentives/disincentives or quotas). The natural progression of a demand response system would be to fix any evident pricing distortions, introduce time-differentiated tariffs, and any other efficiency pricing interventions that tend to flatten peak demand such as pricing of overconsumption of reactive power. Real-time pricing is the next step and requires proper metering and information systems similar to demand time of use pricing. Interruptible tariffs, that offer rebates of price reduction, are also other potential mechanisms.
Changing unit commitment practices	Unit commitment is performed differently in different systems. It may be called generation programming or hydrothermal coordination in other systems. The main strategy is to include variable power sources forecasting to prepare the unit commitment or generation programming schedules. This mainly requires the production of forecasting data and their integration in scheduling algorithms in the EMS systems.
Transmission to access wind and solar resources	Transmission needs to be planned proactively to ensure the needs of the renewables are met in a timely fashion and in a cost-effective matter. Proper pricing of transmission needs to accompany planning so that the best combined transmission and renewable options are developed first. Pricing of transmission should help direct the development of renewables where centrally planned.
Wind curtailment	Requires proper definition of the rules and conditions under which variable power sources will be curtailed. These rules should be followed by all providers as part of dispatch-related grid code compliance aspects. Renewable providers need to consider this implicitly in the designing of their contracts for purchase of energy or in the related mechanisms to receive incentives, which should specify if payments will be made or not under such circumstances.
Improving planning practices	Planning practices need to be adjusted to ensure that the contribution of renewables improve system adequacy and that cost implications are rightly assessed (not over- or underestimated). As variable renewable shares increase, planning needs to encompass potential future implications of short-run operations in order to identify the most cost-effective solutions.

(table continues on next page)

Table 4.1 Strategies to Manage Variability in Grid Operations and Some Prerequisites for Their Application and Effectiveness *(continued)*

<i>Strategy</i>	<i>Prerequisites: technical, institutional, or regulatory</i>
Advances in wind technology	New wind technologies are able to provide services that earlier technologies could not—these include participation in Automatic Generation by increasing or decreasing output within certain limits to respond to system frequency events. These characteristics are valuable as penetration levels increase. Required performance standards that include these new capabilities need to be updated in the grid codes. The utilities, regulator, and private sector need be constantly aware of these new capabilities and analyze the ways in which they can help manage the operational challenges of increased amounts of renewables

Source: World Bank data.

APPENDIX A

Basic Description of Some Solar Technologies

Broadly, two types of solar technologies are being deployed commercially: concentrating solar power (CSP) and photovoltaics (PV). CSP technologies use mirrors or lenses to focus direct normal irradiance (DNI) sunlight onto a small area or receiver. Three different CSP technologies are being pursued commercially. Parabolic troughs use rows of parabolic-shaped reflectors that focus sunlight onto tubes that are positioned along the length of the reflector (see figure A.1). The tubes contain a working fluid such as synthetic oil that, when heated by solar energy, is transmitted to a heat exchanger to heat water and produce high-pressure steam to power a turbine that runs a generator to produce electricity. The best-known example of a parabolic trough system is the Solar Energy Generating System (SEGS) in southern California. The SEGS units were installed in stages in the 1980s and are cofired with natural gas.

A second CSP technology is the central receiver, sometimes referred to as a power tower. Central receivers use a field of receivers (heliostats) that

Figure A.1 Parabolic Trough Systems

Source: NREL 2010.

concentrate sunlight onto a receiver at the top of a tower. The receiver contains a working fluid such as water or molten salt. The molten salt acts as storage to maintain heat that can be used for electricity generation after the sun goes down. As with parabolic troughs, the heated working fluid is sent to a heat exchanger to heat water into steam that then powers a turbine and runs a generator to produce electricity. A 5 megawatts plant operated by eSolar in Lancaster, California, is an example of an operating CSP plant (see figure A.2).

Parabolic dishes (see figure A.3) are the final CSP technology. Individual circular dishes focus sunlight to heat hydrogen or helium gas inside an engine. The heated gas expands, and the pressure from the expansion drives a piston that runs a generator to produce electricity (Kulichenko and Wirth 2011).

The working fluid in CSP have some amount of stored energy. In addition, the production of CSP plants can be predicted minute to minute with a high amount of certainty in the absence of clouds or difficult ground conditions (for example, dust storms). And because of their energy storage capability, the ramps of a CSP plant are not difficult and are also fairly predictable. Finally, a CSP plant will require some time after sunrise to begin generating power as the working fluid heats up, but a CSP plant can produce generation after the sun sets by utilizing the thermal energy in the working fluid.

PV systems (illustrated in figure A.4) generate electricity from solar radiation. The basic element is the PV cell, also called the solar cell. It consists of semiconductor materials that are specially treated to give one layer (the *n*-layer) a negative charge and the other layer (the *p*-layer) when sunlight strikes the solar cell. This sets up a cell barrier (also called the cell junction) between the

Figure A.2 Central Receiver Plants

Source: General Directorate of Electrical Power Resources.

Figure A.3 Parabolic Dish Systems

Source: Renewable Energy Info 2010.

Figure A.4 Photovoltaics System

Source: ISEcology 2011.

semiconductor materials, creating a current. Sunlight striking the PV cell excites the electrons, and the movement of electrons is collected by metallic contacts placed on the cell in gridlike fashion. Materials used for PV systems include monocrystalline silicon, polycrystalline silicon, amorphous silicon, cadmium telluride, and copper indium gallium selenide/sulfide. PV cells are

electrically and physically linked together into modules, and modules are further connected into an array.

Two types of PV modules are available. For flat plate modules, the total surface area of the cells is about equal to the total area of sunlight striking the module. PV systems also use concentrator modules, where a lens or mirror is used to focus sunlight onto a smaller area of cells. PV systems are quite versatile and can be used off-grid, distributed, or in central station applications (NERC 2009).¹

Country Case Studies

China

China's electricity consumption has grown considerably since 2000 due to its rapid economic growth. From 1980 to 2009, annual electricity demand in China grew over 12-fold, from 295 to 3,660 terawatt-hours (Kahrl and others 2011). Electricity consumption in China was 3,643 terawatt-hours in 2009, up by a factor of 3.4 times since 2000 (Cheung 2011), and grew further to 4,200 terawatt-hours in 2010. Peak load in China in 2010 was 658 gigawatts, and installed generating capacity was 962 gigawatts (Qionghui and Xuehao 2011). Projections of future electricity demand by 2020 in China vary widely, ranging from 6,692 terawatt-hours (Cheung 2011) to 11,245 terawatt-hours (Kahrl and others 2011). The former would almost double current demand while the latter would almost triple it.

China occupies a unique place in integrating variable generation, having the most installed wind capacity in the world in an electricity system with limited trading and mostly inflexible generation. China's electricity system is also the world's largest source of carbon dioxide (CO₂) emissions. China has also set ambitious targets for renewable energy that would make it the world's largest market for wind and solar. By 2020 China has set a goal of 150 gigawatts of wind, 20 gigawatts of solar, 380 gigawatts of hydro, and 80 gigawatts of nuclear power. China also wants to get 15 percent of its energy consumption from renewable energy and nuclear power, and to reduce the CO₂ intensity of gross domestic product (GDP) by 40–45 percent by 2020. China is also experimenting with a number of different renewable energy policies. Companies with 5 gigawatts or more of generating capacity must have at least 8 percent of their capacity and 3 percent of their generation from nonhydro renewables by 2020. Feed-in tariffs (FITs) have also been set for wind, biomass, and solar photovoltaic (PV).

Industry accounts for over 70 percent of China's net electricity demand. Among industrial customers, heavy industry accounts for 83 percent of industrial electricity consumption. The high share of industrial load results in a relatively flat load shape in China as compared to countries with higher levels of residential

and commercial electricity usage. As a result, China has historically needed less peaking generation and load following. The high load factor, and the availability of coal resources in China as compared to low available amounts of natural gas and hydro, has also contributed to China's reliance on coal. Although hydro, nuclear, and wind generation in China increased by over sevenfold from 1985 to 2009 (92–669 terawatt-hours), coal still accounts for 78 percent of China's generation mix as of 2009 (Kahrl and others 2011). Coal plants have evolved toward larger, more-efficient plants. The share of units 300 megawatts and higher increased from 23 percent of total thermal generating capacity in 1993 to 69 percent by the end of 2009. The Chinese government has also pushed to shut down small (50 megawatts and less) and old (over 20 years and less than 200 megawatts) units, retiring 60.6 gigawatts of these units between 2006 and 2009.

Natural gas accounts for less than 1 percent of electricity generation in China because of concerns about gas price volatility and the security of supply. Gas is mostly used for residential space heating. China's gas demand is met with the Central Asia–China (Turkmenistan) gas pipeline and with liquefied natural gas (LNG) imports that began in 2006. The State Grid plans to add 43 gigawatts of natural gas plants by 2015, with half located near load centers in Eastern China (Cheung 2011).

China has significant wind resources of 2,380 gigawatts of onshore wind potential and 200 gigawatts of offshore wind potential. Wind capacity in China grew from 300 megawatts in 2000 to about 42 gigawatts in 2010 (see figure B.1). By energy contribution, as indicated in figure B.2., wind provided 0.7 percent of China's electricity generation as of 2009 (Cheung 2011).

China is also embarking on plans to develop seven 10 gigawatts wind power bases over the next decade. Assuming the country meets its 150 gigawatts target by 2020, wind power could provide 4 percent of China's electric generation (Yin, Ge, and Zhang 2011). Other sources suggest that as much as

Figure B.1 Installed Wind Capacity in China, 2000–10

Source: Cheung 2011.

Figure B.2 Electricity Production by Fuel Type in China, 2009

Source: Cheung 2011.

Note: GW = gigawatt; TWh = terawatt-hour, — = not available.

220 gigawatts of wind capacity could be in place by 2020 (Qionghui and Xuehao 2011).

But not all wind capacity in China is interconnected, because of unavailable transmission or grid capacity. Of the wind capacity in place in China in 2010, 6.24 gigawatts was constructed but not commissioned, while another 4.45 gigawatts was under construction and not ready to be interconnected to the grid (Qionghui and Xuehao 2011). Wind curtailment is also significant in China, with wind capacity factors being lower as a result of wind curtailment and insufficient grid capacity. The capacity factor of wind was reported to be 23.7 percent in 2009 (Kahrl and others 2011).

China has the highest installed hydro capacity in the world at 197 gigawatts, but little of it is used to handle variability. About 70 percent of hydro is in central and southern China, while wind is mostly in the far north (Cheung 2011).

Electricity Grid

The electricity grid in China is divided into several regional grids (see figure B.3). The State Grid Corporation operates the northeast, north central, central, east, and northwest regions of China and encompasses 26 provinces in all. The Western Inner Mongolia Grid and the Southern Grid are operated independently from the State Grid.

Figure B.3 Regional Electric Grids in China

Source: Qionghui and Xuehao 2011.

Each grid is responsible for its own profit and loss, and there is little impetus for intergrid cooperation. Therefore, it is difficult for the State Grid to be interested in building transmission to access wind in Western Inner Mongolia, or for the State Grid and the South China grid to cooperate to access hydro in the south. But the grids are responsible for meeting China's renewable energy targets. There are some Direct Current (DC) interconnections among the grids, but power flow among regions and between provinces are limited. Cross-regional electricity transfers were 158 terawatt-hours in 2009, accounting for about 4 percent of total electricity production. Interprovincial electricity imports and exports within a grid cluster were more active at 532 terawatt-hours, 13 percent more than the previous year. Balancing between generation and demand is basically done at the provincial level (Cheung 2011).

Electricity dispatch in China is done using an "equal shares" approach, in which generators of a certain type are guaranteed roughly an equal number of operating hours to gain enough revenues to recover their fixed costs. The approach is economically and environmentally inefficient as low-efficiency generating units (high heat rates) may have the same number of operating hours as those units with low heat rates. China has experimented with environmental dispatch rules to prioritize renewables and clean coal generation.

China does not have a structured and transparent means of linking costs and retail electricity prices. Wholesale generation rates in China are roughly based on average costs. China uses a benchmark price that sets uniform prices for

generators based on industrywide technologies and expected performance, as well on estimates of annual output and fixed and variable costs. Because of benchmark pricing, generation supply curves are typically pretty flat in China. Wholesale prices for renewable generators are set using a provincial benchmark price plus a national renewable energy subsidy. Rates for hydro, coal, and nuclear are set on a plant-by-plant basis. Ancillary services are required from generators with most ancillary services provided by a few power plants (Kahrl and others 2011). Money is collected from all coal plants and paid to the plants that provide the ancillary services. China is in the midst of assessing the projected ancillary service impacts of wind.

More than 80 percent of the electricity trading between regions and provinces is handled under long-term contracts, where the quantity and prices of electricity traded are annually based on demand and supply forecasts. The central government, provincial governments, and grid companies participate in the negotiations. Less than 20 percent is traded in the spot market and usually reserved for cases of emergency. The majority of electricity trading is based on yearly agreements among provinces, with actual trading (timing and amount) reviewed weekly or monthly. Electricity trading, therefore, is quite rigid, with the tradable amount capped and prices fixed while demand and the export capacity of a province can change over time (Cheung 2011).

In regions without hydro, coal is used for load following and peaking, resulting in significant cycling of coal units and reducing the efficiency of those plants. Most of these services are provided by natural gas in other countries. Coal is also used to supply ancillary services, including spinning and nonspinning (Kahrl and others 2011).

Further adding to the complexity of integrating variable energy generation in China is the fact that energy resources are concentrated in regions far from electric demand centers. Two-thirds of wind and solar resources are located in north and northwest China, and 80 percent of the country's hydro resources are in southern China, but the majority of electric demand is located in eastern and central China. This geographic concentration of energy resources, combined with the limited interconnections and trading between provinces, can make variable energy integration challenging, as is indicated in figure B.4. In 2010 the installed capacity of wind as compared to peak load was as high as 82 percent in East Inner Mongolia, while that same region received over 20 percent of its electric generation from wind.

Wind production is typically nearly opposite that of load (that is, wind is high when load is low and vice versa), and that is the case in China as well. Because of minimal interconnections and trading between provinces, wind production can be higher than that of load during certain hours. Figure B.5 shows a daily pattern of wind, load, and net load from an unspecified day. Wind production nearly matches load in the early morning hours before dropping off while load increases.

As noted earlier, thermal generation in China tends to be inflexible. In most of the wind-rich regions in China, combined heat and power (CHP) units

Figure B.4 Percentage of Wind by Peak Demand and by Energy Contribution for Different Regions in China, 2010

Source: Qionghui and Xuehao 2011.

Figure B.5 An Example of Daily Load, Net Load, and Wind Production in China

Source: Qionghui and Xuehao 2011 (unspecified region of China).

account for much of the local generation mix and is needed to provide heat in addition to generation. High wind production during low-load periods can aggregate minimum load concerns and results in considerable wind curtailment.

The China Electric Power Research Institute designed and implemented a day-ahead wind forecasting system in Jilin; mean square root errors for the

day-ahead forecast ranged from 11.05 percent to 19.08 percent (Yin, Ge, and Zhang 2011). Wind forecasting has since been implemented in 12 regional and provincial power companies in the north and northeastern grids of China, covering about 15 gigawatts of wind capacity. China recently has required all wind generators to provide a wind forecast by July 2012.

The State Grid also developed the National Wind Power Research and Inspection Center in December 2010 (Qionghui and Xuehao 2011). China is also in the midst of implementing a grid code for wind that requires wind turbines to meet low-voltage ride-through standards. Finally, China is building transmission to interconnect more wind capacity to load centers, including for the seven 10 gigawatts wind bases. By the end of 2010, China has expended over 41.8 billion RMB for transmission for wind projects. One ultrahigh Alternating Current (AC) voltage transmission line and one ultrahigh Direct current (DC) voltage transmission line are now operating in China, and more are scheduled to be constructed over the next 10 years to interconnect the wind power bases (Yin, Ge, and Zhang 2011).

Germany

Germany has a long history of policy support for renewable energy development and, as of end 2010, had 27.2 gigawatts of wind capacity (German Federal Ministry for the Environment 2011). Peak demand in Germany is approximately 80 gigawatts, while minimum demand can be as low as 30 gigawatts, leading to high levels of wind penetration during off-peak nighttime hours. The main mode of support has been a FIT that offers guaranteed payments for renewable energy output. Due mainly to the FIT, the vast majority of renewable energy development, including wind power, has been on a smaller scale and hence connected to the distribution rather than the transmission system. In the last few years, however, Germany has reached the point where good land-based sites are in shorter supply and therefore the focus has shifted to developing Germany's offshore wind resources. It is anticipated that the majority of future wind development will be mainly large scale, transmission system connected, and offshore, located in northern Germany.

Grid Code

Due to the strong growth in wind power in northern Germany, Transpower (as E.ON Netz) was one of the first grid operators in the world to develop grid codes specific to wind. These codes have been revised several times and adopted by other German transmission system operators (TSOs). The grid codes require wind generators to withstand and ride through voltage drops of up to 15 percent for 625 milliseconds, and to provide grid support and reactive power for up to 3 seconds (Porter 2007). All wind facilities (and other generators) are required to have approved switchgear and reactive power exchanges, keep operating during system disturbances, and keep

voltage and frequency within a specific range. Older wind facilities used to be exempt from these requirements. Recently, however, Germany has instituted a repowering program, where these older wind turbines are being replaced and wind facilities need to conduct retrofits to meet the voltage drop and ride-through requirements. Germany has also instituted voltage ride-through requirements for solar PVs.

Electricity Market

Balancing Reserves

The German TSOs utilize three types of balancing reserves. The primary regulation reserves, equivalent to frequency responses, are automatically controlled generation that respond to frequency variations. All TSOs in Europe are required to provide 3,000 megawatts of primary reserve capacity that can begin operating within 30 seconds. The 3,000 megawatts is equal to the outage of two major nuclear plants, each with a capacity of 1,500 megawatts; the German share is 630 megawatts. The secondary reserves, equivalent to regulation, are up-and-down regulation reserves that can be deployed within 5 minutes. The German TSOs acquire about 4,900 megawatts (–2,200 megawatts for regulation down and 2,700 megawatts for regulation up). This is provided mainly by hydropower and pumped storage hydro plants. The tertiary reserves, equivalent to load following, must be available within 15 minutes (Ernst and others 2010). German TSOs acquire –2,400 megawatts of downward tertiary reserve capacity and 2,300 megawatts of upward tertiary reserve capacity. In addition, 50 Hertz also requires that “renewable energy substitutes” be available to help smooth fluctuations in energy supply, in particular from wind power. These are prequalified energy resources that are able to provide positive and/or negative primary, secondary, and “minute” reserves.

Since 2009 three of the four TSOs have shared in an optimized shared secondary reserve system that economically dispatches plants to balance energy in the entire three-TSO area. Table B.1 shows the estimated reductions in reserves through the shared secondary reserves market. The fourth TSO is now also participating in the shared secondary reserve system.

Germany operates as a single-price-area energy market, which includes a day-ahead, an intraday, and reserves markets. All wind energy in Germany must be sold on the spot market known as the Energy Exchange (EEX) and settled every 15 minutes. TSOs pay wind energy suppliers the FIT price and put the wind

Table B.1 Reserve Reductions through Shared Secondary Reserve System (MW)

<i>Type of reserve</i>	<i>Up reserves</i>	<i>Up reserves after</i>	<i>Down reserves before</i>	<i>Down reserves after</i>
Primary regulation	135	135	n.a.	n.a.
Secondary reserve	630	532	–450	–464
Tertiary reserve	350	288	–756	–532

Source: Ernst and others 2010.

Note: n.a. = not applicable.

energy on the EEX. As noted earlier, all wind energy is pooled amongst the TSOs, and energy and costs are equalized based on the real-time redistribution of the wind energy and associated imbalances in proportion to the load shares in each control area. The TSOs are responsible for balancing the difference between their 15-minute shares of wind energy and their share of actual wind power production (Ernst and others 2010).

Transmission System

There are four German transmission system operators (TSOs): Transpower Stromübertragungs GmbH (Transpower, formerly E.ON Netz), Amprion GmbH, 50 Hertz Transmission GmbH (formerly Vattenfall), and EnBW Transportnetze AG (see figure B.6).

In compliance with the German law, each of the TSOs is obligated to take all electricity generated from renewable energy sources within their control area and

Figure B.6 German TSO Territories

Source: Neumann 2010.

compensate the generators for their electricity at the established FIT rate. The amount of renewable energy produced and put onto the German grid is pooled in a common electricity market and balanced among the four German TSOs. Therefore, the cost of purchasing the renewable energy is shared equally by the four TSOs, even though two of the TSOs (50 Hertz and Transpower) have substantially more wind power facilities connected to the grid. The TSOs are also responsible for investing in transmission system development and balancing the deviations for their portion of renewable energy.

Transmission Overloads

High wind output can lead to loop flows from north to south and east to west within Germany, and with countries such as Poland, Austria, Belgium, and the Czech Republic. France and the Netherlands have installed phase-shifting transformers to prevent loop flows through their systems. Available transmission capacity at the borders between Germany and other countries are adjusted daily based on advance forecasts of wind power. Transmission congestion is handled through redispatch of power plants to manage overloads, and if necessary, plant curtailments, including wind. Generators that are redispatched because of high wind production are paid for any lost revenues, including start-up and shut-down costs (Ernst and others 2010).

Planning and Forecast

In 2005 the German Energy Agency (dena) released the first *Planning of the Grid Integration of Wind Energy in Germany Onshore and Offshore up to the Year 2020* (dena Grid Study I). The study examined scenarios for the increased use of renewable energy sources for the years 2007, 2010, 2015, and 2020, and identified current and projected inadequacies in the power system while compiling a list of needed electric grid upgrades that would be required to uphold Germany's projected renewable energy development by 2015. This included 850 kilometers of new transmission construction. In August 2009 the German Legislature passed the Power Grid Expansion Act (EnLAG) to facilitate and accelerate the construction of new transmission lines. The EnLAG prioritized 24 of the dena Grid Study I expansion projects. In 2010 the dena Grid Study II was released, which examined electricity needs and solutions for having renewable energy account for 39 percent of total German energy supply by 2020. This study examined transmission options using traditional (Basic) and new technologies including: high temperature resistant aluminum conductors (TAL), flexible line temperature management systems (FLM), high-voltage DC lines (HVDC), a combination of the three (hybrid), and a universal use of underground lines (GIL) (see figure B.7).

Other planning initiatives included expanding the use of electricity storage, including a dena program for using the natural gas grid. Excess electricity would be used to produce hydrogen, which could then be fed into the natural gas network or processed into synthetic gas and stored for later use.

Figure B.7 dena Grid Study II Transmission Scenarios

Identified grid expansion and annual costs for the investigated variants.

Source: dena Project Group 2010.

Note: FLM = flexible line temperature management systems, GIL = underground lines, HVDC = high-voltage DC lines, TAL = temperature-resistant aluminum conductors, km = kilometer.

To facilitate offshore wind development, the German government pursued the idea of an offshore grid in the North Sea, and is working together with the other North Sea border countries. The North Sea Countries' Offshore Grid Initiative (NSCOGI) includes 10 countries around the North and Irish Seas: Belgium, France, the Netherlands, Luxembourg, Germany, the United Kingdom, Ireland, Denmark, Sweden, and Norway. The NSCOGI aims to work together to coordinate offshore wind and infrastructure developments. The plan is to develop a coordinated North Sea grid and clustered offshore wind facility connections (German Federal Ministry of Economics 2010).

Wind Forecasting

The German TSOs utilize several forecasting services at the same time and use a weighted sum of these forecasts adjusted to observed weather patterns. For example, Amprion uses 10 different wind forecasts that are entered into a "combination tool," which then produce an optimal forecast taking into account the weather situation. Fifty Hertz combines three different forecast tools to create a weighted sum forecast for the TSO's area and for Germany as a whole (Ernst and others 2010). The combination of forecast models takes advantage of the fact that these models deal with weather situations differently, with some being better under specific conditions while others are better predictors under different conditions. Due to the implementation of these aggregate forecasting methods, the day-ahead wind power production forecast root mean square error for Germany as a whole averages about 4.5 percent (European Wind

Energy Association 2010). TSOs sell the day-ahead forecasted amount into the day-ahead spot market; they also sell the difference between the day-ahead and intraday forecast into the intraday spot market. Any remaining deviations are covered by balancing reserves.

Spain

Nearly all of the electricity consumed in Spain is generated domestically, with less than 1 percent imported from outside the country. As indicated in figure B.8 fossil fuels generate approximately 31 percent of the electricity produced in Spain, with nuclear contributing about 22 percent, wind 15 percent, hydroelectric facilities 14 percent, solar 2 percent, cogeneration and other renewables 15 percent, and other fuels making up about 1 percent of the total amount of electricity generated (Diaz 2011). Spain has a peak demand of about 45 gigawatts and an off-peak demand ranging between 19 and 25 gigawatts. Wind energy penetration has been as high as 54 percent, as observed in August 2009 (López 2010).

Spain had about 20 gigawatts of wind power capacity as of end 2010, placing them fourth in the world by amount of installed wind capacity after China, the United States, and Germany (GWEC 2011). Growth in wind power capacity in Spain has slowed in recent years, with 1.5 gigawatts of wind capacity installed in 2010 (McGovern 2011). To comply with the European Council directive that 20 percent of energy consumption be supplied by renewables by 2020, Spain will need to install 40 gigawatts of wind, including 5 gigawatts of offshore wind capacity (Smith and others 2010). Spain also has set a solar PV target of 10 gigawatts by 2020 (REN21 2011). Because of budget issues and the economic recession, Spain imposed an annual cap on solar installations of

Figure B.8 Electricity Generation and Capacity by Source in Spain, 2010

a. Installed power (as of December 31, 2010)

b. Demand coverage 2010

Source: Diaz 2011.

500 megawatts for 2009 and 2010, and 400 megawatts for 2011 and 2012 (Kreycik, Couture, and Cory 2011). This has resulted in a drop in installed solar capacity in Spain from 2,600 megawatts in 2008 to about 100 megawatts in 2009 and 400 megawatts in 2010 (Gipe 2010; REN21 2011).

Electricity Market

The Spanish Electricity Market is organized as a sequence of markets: the day-ahead market, four intraday markets that operate close to real time, and the ancillary services market. Participation in these markets is not compulsory (as participants are allowed to enter into physical, bilateral contracts outside the market structure), but most transactions are carried out in the daily market. Available production units that are not linked to a bilateral contract participate as sellers. The price to be received or paid by the participants is set according to a uniform-price auction. Therefore, irrespective of individual bids, the market-clearing price is set equal to the highest accepted supply bid, or the “System Marginal Price” (Crampes and Fabra 2004). Buyers on the daily market include regulated distributors, retailers, resellers, qualified consumers, and external agents registered as buyers.

Generation in Spain is classified as under the ordinary regime, special regime, or renewable nonmanageable. Generators under the ordinary regime sell their production on the wholesale market and receive compensation for the electricity sold, plus a capacity payment. Special regime generators are no more than 50 megawatts and consist of high-efficiency cogeneration, nonrenewable waste, and nonconsumable renewable energies, biomass or biofuels. Renewable nonmanageable generation includes energy sources that cannot easily control their generation output in following system operator directions, and whose expected future output is not certain enough to be scheduled, although it can be forecasted. Red Eléctrica de España (REE) conducts tests to classify whether a specific facility is considered manageable or nonmanageable.

All generators, including wind and solar, are responsible for the costs of any schedule deviations and for paying for the costs of the balancing energy necessary. A penalty is applied if the individual plant’s scheduled deviations are opposite to grid needs. Therefore, if a generator generates less than is scheduled, it pays the market price for balancing generation if the deviation supports the grid or the maximum “up reserve” price if the deviation is not in support of the grid. If a generator generates more than is scheduled, they pay the balancing cost for a generator not to produce and are paid the market price if the extra generation is in support of the grid, and the minimum price if not (López 2010).

Transmission System

As one of the first European countries to initiate electricity market liberalization policies, Spain privatized and unbundled the transmission system in 1985 and passed the European Union’s Electricity Sector Act by Royal Decree in 1997. REE is the Spanish transmission operator, owned both by the Spanish government and

privately. REE has over 34,000 kilometers of transmission lines (López 2010). The Compañía Operadora del Mercado Español de Electricidad, S.A. (OMEL) was created by the Spanish government to manage the business side of the electricity market, establish a spot market, operate the futures market, and assure the timely settlement of payments. Thus, REE was placed in charge of the technical operations and OMEL the economic functions of the market.

REE has been the main transmission owner since it was created in 1985 and is a private firm regulated by the *Comisión Nacional de Energía* (CNE). Royal Decree 1955/2000 guarantees access to the transmission system. Other relevant orders include Royal Decree 2819/1998, which defines the economic scope of transmission and distribution activities to guarantee a high degree of service quality; and Royal Decree 1164/2001, which fixes the tariff rules for access to the networks of transmission and distribution of electricity (Crampes and Fabra 2004).

As the system operator, REE performs the following functions:

- Receives information from producers regarding available energy
- Generates demand projects based on information from distributors, marketers, consumers, and internal resources
- Analyzes technical constraints
- Evaluates the need for reserves
- Establishes an hourly generating program for each one of the systems
- Plans the development of the transmission grid
- Manages interconnection requests and access to the grid.

Spain has several high-voltage transmission interconnections with France, Portugal, and Morocco, but unlike Germany and Denmark, Spain's interconnection to the rest of Europe is relatively weak, with between 2,000 and 3,000 megawatts of cross-border capacity. Therefore, most supply-demand balancing is done internally.

REE is planning to invest €8 billion through 2016 in transmission and distribution improvements (Smith and others 2010). About 20 percent of the cost is related to integrating more renewable energy generation (Díaz 2011). These improvements include 3,504 kilometers in new 400 kilovolt transmission lines and 961 kilometers in 220 kilovolt transmission lines, as well as the refitting of 3,850 kilometers of 400 kilovolt lines and 4,458 kilometers of 220 kilovolt lines. Load-flow and transient stability studies were done to determine whether the higher levels of wind and solar generation can be accommodated, and concluded that they can be incorporated if:

- The planned transmission and distribution system improvements are completed by 2016
- The wind and solar generators comply with technical requirements, and the grid code is strengthened

- Wind and solar generation can provide dynamic voltage control
- Reserves are available to handle valley demands (Smith and others 2010).

Impact of Solar Power on the Grid

Generation from solar PVs has increased in Spain from 40 gigawatt-hours in 2005 to 5,347 gigawatt-hours in 2009. Only 2 percent of solar PVs is connected to the transmission grid in Spain; the remainder is connected to the distribution grid and cannot be observed by REE, which REE says “must be solved” (López 2010). Because winter peak is in the evening, solar PVs does not contribute to winter peak demand, but follow summer demand requirements. Solar thermal projects with molten salt storage or combined with natural gas contribute to winter and summer peak demand, with 54 percent of capacity connected to the transmission grid and the remainder connected to the distribution grid (López 2010).

Spain has 3.8 gigawatts of solar PVs, although only 400 megawatts was added in 2010 because of a cap on ground-mounted systems and because of market uncertainties with future solar regulations. Even so, Spain is the second-leading country in the world in PVs installed capacity behind Germany. Spain is the world leader in concentrating solar power (CSP) capacity, with 632 megawatts installed as of end 2010, 400 megawatts of which was installed in 2010. Another 946 megawatts of CSP capacity is under construction, and Spain is expected to have a total of 1,789 megawatts in CSP by the end of 2013 (REN21 2011). For both PV and CSP, the average capacity factor is about 16 percent.

Nearly all of the PV capacity in Spain is connected to the distribution grid, while 70 percent of CSP is connected to the transmission grid. Lack of grid operator awareness of solar PV is considered a problem, as PV plants are not required to send real-time production and operation information to REE. Spain currently only has real-time measurement data of about 150 megawatts of PV power and uses meteorological predictions to estimate how much solar PV exists each hour, whereas it has real-time information of all CSP plants.

Currently, variability of solar PV production does not exceed that of load and is not considered to be an issue for secondary regulation. The geographic diversity of solar has also helped, as solar PV plants have been installed nearly everywhere in Spain except for the northernmost provinces.

Solar PV is having a larger impact on slower reserves at certain times, as solar during a cold, sunny winter day can be as high as 2,500 megawatts during the middle hours of the day, but decreases rapidly as the sun sets and as demand rises. Down reserves may be short in supply if solar, wind, and hydro are at high production during the middle hours of the day, as thermal generation needed to meet peak must be online.

Solar PV does not have the ability to ride through voltage drops, although because solar PV is mostly connected to the distribution grid, they are not as vulnerable to faults on the transmission system. In addition, the use of converters means solar PV systems are not as sensitive to voltage drops.

Nonetheless, Spain is considering amending its grid code to apply to solar systems (NERC 2010a).

Spain coordinates forecasting and scheduling of solar plants, and although early indications suggest that solar forecast accuracy is not very good 6 hours in advance, the forecast error is tolerable because of the coincidence of solar with peak demand. One example is the solar forecast inaccuracy from the 12.3 megawatts Guadarranque solar PV plant, which was about 50 percent from August 2009 to September 2010, with the lowest value being 25.4 percent. But in an example of diversity of solar production among multiple solar PV plants, the aggregated data from over 70 solar PV rooftop installations showed average deviation of less than 1 percent from expected solar generation (Chandler 2011).

Impact of Wind Power on the Grid

REE has identified the following challenges with integrating higher levels of wind generation:

- *Wind production is not correlated with electricity demand.* Wind generation may occur at different times than when electricity is needed, particularly in summer. According to REE, the maximum contribution of wind to winter peak demand is about 4 percent, and 1.5 percent in summer.
- *Wind generation will trip if wind speeds exceed 25 meters per second.* Spain adopted a grid code that requires wind turbines to ride through faults shorter than 100 mili seconds and to survive voltage drops lower than 85 percent per unit (p.u.) About 85 percent of wind capacity in Spain can meet the fault ride-through requirements.
- *The variability of wind generation can be problematic.* REE states that wind upward and downward ramps can be 1,500 megawatts per hour, but wind forecasts help mitigate this issue to some degree.

Wind developers seeking to sell their output on the wholesale market in Spain must arrange for interconnection to the transmission system. Royal Decree 1955/2000 and Resolution 3419 issued on February 11, 2005, govern the procedures through which facilities can apply for an interconnection. Facilities to be connected at greater than 100 kilovolt must request access from REE, even if a local distribution utility owns the node to which access is connected. If access is requested through a distribution system, the developer will apply for an interconnection to the local utility managing the distribution system who will subsequently request access for any additional load that will occur from the local distribution system to the transmission system as a result of the project. REE maintains a list of interconnection requests from potential wind projects.

REE is impacted in two ways from a new wind facility. First, under current regulations, REE will have to purchase the output of any facility operating under the special regime. Second, REE will manage the technical operation of the grid, including management of imbalances or voltage reductions that may result from

unexpected wind conditions. Under Royal Decree 436/2004, wind producers using the market tariff already schedule their load on the wholesale market, buying and selling excess power as needed to smooth out any imbalances. Those participating under the fixed tariff rate are required to forecast and schedule their projected electricity supplies.

Wind companies are required to use their best forecast, offer all their production, update intraday schedules according to revised wind forecasts, and pay for any balancing energy needed to offset deviations from the schedule (López 2010). Spain has more than 700 wind projects with different owners, each having different requirements for operation, switching, and maintenance. REE has had trouble contacting wind plant owners for emergency generation reductions, plant outages, or maintaining transmission assets near generation interconnection points. Spain therefore requires wind projects over 10 megawatts to be associated with a control center to communicate directly with REE, with wind generators bearing the cost. The control center is to be connected to the Control Center for Renewable Energies, known as the CECRE in Spain, that in turn is connected to REE. The CECRE handles special regime generation and is particularly focused on wind power. REE can control wind generation by sending orders from REE's control system to the wind generator's control center. The wind projects are aggregated into wind clusters, with one cluster for each transmission system node. It analyzes maximum wind generation that can be accommodated in real time and sends directives to wind generators if curtailments are needed. Wind generators must adjust their production to required set point within 15 minutes. This is only done for wind generation but can be extended to other renewable energy technologies as well (López 2010).

Over 70 percent of Spain's wind capacity is connected to REE's transmission network, allowing REE to monitor wind production. REE uses a central wind forecast for all wind generation, which provides hourly wind forecasts for the next 10 days, and a forecast by transmission system node that is updated every 15 minutes for the next 48 hours. Confidence intervals at 15 percent, 50 percent, and 85 percent are provided, with the 85 percent level used to determine if there are enough units committed. REE uses an ensemble of five independent wind forecasts (NERC 2011) and observes that improvements in wind forecasting have resulted in fewer reserves needed to account for wind forecast errors, particularly at the day-ahead time scale.

REE reports that the mean average error for hourly wind forecasts for the next 10 days ranges between 10 percent and 15 percent for day ahead to about 30 percent from 5 days ahead to 9 days ahead (López 2010).

To accommodate 40 gigawatts of wind capacity long term, REE states that wind generators will need to have the technical capability to provide frequency control, primary reserves, and inertia. Additional interchange exchange, very flexible gas turbines, additional pumped hydro storage, improved wind and solar forecasting, and using demand side management to ease integration would also be helpful (López 2010).

Reserves

REE evaluates the need for reserves through continuously running a probabilistic function with demand forecast error, wind power forecast error, and thermal generation outages, with different confidence levels ranging from 80 percent to 99 percent (López 2010). Four types of reserves are utilized in Spain: primary (roughly equivalent to regulation), secondary (roughly equivalent to load following), tertiary, and ramping (also called “hot reserves”). Primary reserves are required in Spain and are a nonpaid service by all conventional generation units (Milligan and others 2010a). Generators with primary reserve responsibility operate with a reserve margin of 1.5 percent, must respond to frequency deviations within 30 minutes, and be sustained for 15 minutes. Wind generation has had no impact on primary reserves (NERC 2011).

Secondary reserves are provided by generators on automatic generation control (AGC). REE purchases up to $\pm 1,500$ megawatts of secondary regulation reserves for system balancing in real time. About 16 gigawatts of quick response hydro capacity is also included in the secondary reserves (Milligan and others 2010a). Generators providing secondary reserves must respond within 2 minutes and be able to operate at a sustained level for 15 minutes. Wind generation has had little impact on secondary reserves, as wind ramps coincide with system demand. Spain has not had to acquire additional secondary reserves due to high levels of wind and solar generation (NERC 2011).

For tertiary reserves, generators must respond within 15 minutes and operate at sustained level for up to 2 hours. Tertiary reserves are used for manual generation adjustments to meet changes in generation and load (Milligan and others 2010a). Tertiary reserves are dispatched 15 minutes before the beginning of the operating hour, or within the hour as required. Tertiary regulation is an optional service but with a mandatory bid, with compensation determined by market mechanisms. Presently, wind generation affects the level of tertiary reserves modestly and only if wind ramps are opposite that of system demand (NERC 2011).

Ramping or hot reserves can be called upon within 15 minutes and must be capable of sustained operation for up to 2 hours. Ramping reserves include tertiary reserves, the reserves of operating thermal units, and reserves of hydro and pumped storage hydro plants. Wind forecasting errors have increased the need for ramping reserves (NERC 2011).

REE reports that both up and down reserves may be insufficient in certain hours due to outages of conventional generation, demand prediction errors, wind or solar forecast errors, wind units tripping because of high wind, or inflexible generation. If up reserves are insufficient, REE may commit additional thermal units through real-time dispatch; if there are insufficient down reserves, then REE may decommit thermal units in real time. If down reserves are still insufficient, REE curtails nonmanageable renewable generation as a last resort (López 2010).

Table B.2 provides the amount of energy, in gigawatt-hours, that REE has procured for different ancillary services between 2007 and 2010, as well the energy subject to deviation management and restrictions in real time.² The secondary

Table B.2 Reserves and Managed Energy for REE in Spain 2007–10*gigawatt-hour*

	2007		2008		2009		2010	
	Increase	Decrease	Increase	Decrease	Increase	Decrease	Increase	Decrease
Secondary regulation band	718	520	717	526	718	526	727	531
Secondary regulation	949	1,188	1,127	1,123	1,072	1,406	1,165	1,724
Tertiary regulation	1,752	2,107	2,450	2,008	2,238	3,287	2,726	2,983
Deviation management	829	1,330	1,190	997	1,253	3,018	2,198	2,675
Restrictions in real time	864	358	620	596	821	640	887	901

Sources: REE 2009, 2011.

regulation band has stayed relatively flat, while secondary regulation has risen between 2007 and 2010 in both the increasing and decreasing direction. Tertiary regulation has also gone up in the increasing direction between 2007 and 2010, while tertiary regulation in the decreasing direction rose between 2007 and 2009 but dropped back in 2010. Deviation management in both directions has more than doubled between 2007 and 2010, while restrictions in real time in the decreasing direction more than tripled while remaining relatively flat in the increasing direction, also between 2007 and 2010.

Figure B.9 depicts the costs REE has paid for “adjustment services” that REE defines as services needed to ensure the reliability of electric services and which include ancillary services and deviation management. The costs spiked in 2006, but have otherwise risen slowly from €2.3 per megawatt-hour in 2004 to €2.7 per megawatt-hour in 2009, before increasing to €3.9 per megawatt-hour in 2010 (REE 2009, 2011).

Figure B.9 Adjustment Energy Costs in Spain, 2004–10*euros per megawatt-hour* *Sources:* REE 2009, 2011.

Reactive Power and Grid Codes

Until January 2009 Spain provided bonus payments or penalties for reactive power as determined by the actual power factor and the time of day. The payment was a percentage of the market and premium price and varied from –4 percent for a power factor of less than 0.95 at peak- and flat-rate periods to an 8 percent bonus for a power factor of less than 0.95 inductive in valley periods or less than 0.95 capacitive in peak-rate periods.

But the incentive payments did not distinguish between workdays and holidays, so generators sometimes did not act in the best interests of the grid. Beginning in January 2009, all special regime generators over 10 megawatts are required to maintain an inductive power factor between 0.98 and 0.99 (López 2010).

In October 2006 Spain adopted a grid code that required wind turbines to stay operating if voltage drops to 20 percent of nominal voltage lasting up to 500 milliseconds, followed by a ramp up to 80 percent of nominal voltage in another 500 milliseconds, and a more gradual recovery to 95 percent of nominal voltage 15 seconds from the occurrence of the grid fault (Fernández 2006). About 85 percent of the wind capacity in Spain is certified as compliant with this grid code. REE is working on drafting changes to the grid code that would have new requirements for staying online due to changes in voltage and frequency (Asociación Empresarial Eólica 2010).

Wind Curtailment

Under its interconnection agreements with wind projects, REE can curtail wind production if system conditions require such action. Wind curtailment has increased in recent years in Spain. Curtailment may occur because of transmission congestion, insufficient reserves, or maintenance of system stability during voltage dips or tripping of wind generators from high wind speeds. To address congestion, REE redispatches in order of: conventional plants, nonrenewable management generation under the special regime, renewable management under the special regime, nonrenewables and nonmanageable under the special regime, and renewable nonmanageable special regime. If renewable nonmanageable generation must be curtailed, then generators must adapt their production to the given dispatch point within 15 minutes. If there are more than 3 reductions in a month or more than 10 reductions in a year, then REE must develop an investment plan to address the constraint (López 2010). Variable generation receives 15 percent of the projected energy payment if it is curtailed in real time to maintain reliability (NERC 2011).

Organizing a Grid Operational Integration Study to Approximate Short-Term Reserve Needs³

Integration studies have been done at different times and have not necessarily been tied to the amount of wind or solar power that has been developed. Generally, utilities in the United States have done integration studies in advance of wind capacity being installed because of concerns higher variability and uncertainty, while European countries have installed wind capacity and employed a “connect and manage” approach before doing wind integration studies. If a utility or grid operator has some or all of these characteristics—flexible generating resources, adequate transmission, large balancing area, and geographically diversified wind and solar projects—then very small amounts of variable generation (<10 percent) can be incorporated without too much difficulty and using a “connect and manage” approach (Chandler 2011). Utilities or grid operators without these favorable system characteristics will not be able to incorporate as much variable generation without using some of the strategies discussed earlier. Forecasting then becomes critical even at small penetrations, especially if more wind and solar generation is expected (Miller 2008). The International Energy Agency (IEA) is developing a spreadsheet model to help countries and regions determine the available flexibility on their systems to accommodate variable generation (Chandler 2011).

A wind and solar integration (or, alternatively, variable generation) study typically identifies the operational and reliability issues from increasing levels of wind and solar penetration by energy. Usually, multiple scenarios of different wind and solar penetrations are studied, ranging from a baseline of current wind and solar penetration to levels of 10 percent, 20 percent, and/or 30 percent. At each level of wind and solar generation that is studied, variations in production costs, changes in reserve requirements, and the flexibility of existing generation assets to operate at different set points are evaluated. A variable generation study will not provide a maximum level of wind and solar generation that can be incorporated, as high levels of wind and solar

generation can be integrated if grid operators, policy makers, and regulators are willing to take the necessary steps of undertaking mitigating actions, incorporating forecasting, and procuring additional reserves if necessary. Furthermore, variable generation integration studies are not substitutes for detailed transmission studies and plans, nor are they substitutes for the interconnection studies that are done to determine the reliability impacts of hooking a proposed generator to the grid. Those detailed transmission and interconnection studies evaluate specific individual transmission projects or generation plants, while a variable generation integration study examines potential scenarios of higher levels of wind and solar capacity from an aggregate, systemwide perspective.

Variable generation integration studies are typically data and labor intensive and can take a year or more to compile. There are several components to a variable generation study:

- *Production cost modeling* for hourly simulations of power flows, costs, and dispatch
- *Statistical analysis* for determining hourly deviations in net load from adding wind and subhourly variations
- *Capacity value and reliability analysis* for assessing the capacity value of wind and solar generation
- *Load-flow analysis* for determining the transmission flows that occur with higher levels of variable generation, evaluating congested transmission flow-gates, and determining the transmission additions that are needed. The transmission system is studied both unconstrained (under a “copper sheet” analysis) and constrained
- *Sensitivity studies*, such as assessing the impacts of different fossil fuel prices, different fuel mixes, higher or lower projected electricity demand, different operating levels of coal plants (more flexible versus less flexible), different levels of hydro flexibility (again, more flexible versus less flexible), and varying accuracy of forecasts of variable generation.

Figure C.1 illustrates how a typical variable generation study is structured and sequenced.

Variable generation studies are data and time intensive, involve multiple organizations, and can typically take a year or more to do. Ideally, a single organization organizes and leads the study, with help from other organizations and a study technical review committee as needed. Although variable generation studies can be conducted in-house, they are often contracted out to multiple consultants with expertise in power systems, transmission load flows, and variable resource production and forecasting.

Data to be included in a variable generation study are for at least one year and preferably multiple years. The study includes time-synchronized wind, solar, and load data to capture interannual variability of load and wind. Load

Figure C.1 Sequence of a Typical Variable Generation Integration Study

Source: Enernex Corporation 2010.

Note: ELCC = electricity load carrying capability; LOLE = loss of load expectation; NREL = National Renewable Energy Laboratory.

forecasts for multiple years are needed to compare the performance of load forecast. Subhourly load and generation data (minute by minute, 10 minute) are needed for analysis of interesting periods (high wind, high load, high wind/low load, high solar/high load, high solar and wind/high load, and so on) and to determine the subhourly requirements for ancillary services such as regulation. Finally, projected variable generation data and forecasts are compiled using a mesoscale numerical weather prediction model. Wind forecast errors are simulated by imposing a random error on top of wind generation profiles, or by comparing the simulated wind forecast with actual wind forecast errors of the same time frame, and counting the difference between the two as wind forecast errors.

Current and projected transmission load flows are needed to estimate whether additional transmission will be needed, and if so, where. Study designers will need to decide whether to conduct detailed transmission studies for low- and high-voltage transmission levels.

Ideally, study inputs, assumptions, data, and results should be public and transparent, though nondisclosure agreements on individual data sets may be necessary. In addition, a technical review committee to devise study scenarios, research and provide data, and provide technical assistance and review are a common feature of grid integration studies. The technical review committees serve complementary functions of providing information on local or regional grid-operating practices and procedures, as well as a conduit for information exchange on wind and solar integration between the study participants and technical review committee.

Simplified Methods of Estimating Impacts of Variable Generation in Short-Term Reserves

Variable generation studies require large amounts of data on current and expected load demand of wind and solar generation on both hourly and sub-hourly time scales for multiple years. These studies also are time intensive and can take about a year to conduct. They require load-flow models for simulating transmission flows and production-cost models to simulate hourly plant dispatches, electricity costs, and emissions. Some countries or regions may not have the available data or resources to perform a detailed variable generation study, yet if they are expecting additional variable generation capacity, they need to approximate the amount of reserves that may be needed. It should be noted that these approximation methods only encompass a subset of integration issues, namely (1) quantifying the balancing reserves needed to manage wind variability and uncertainty in the day-ahead to minute-to-minute time frame and (2) estimating the cost of holding resources in reserve. These approximation methods are derived from older research that was performed before the more-sophisticated integration studies with production simulation and load-flow models, but seem to capture some of the important features when it comes to estimating short-term balancing reserves and the cost of holding resources in reserve. They will not, however, provide the information of a full-fledged integration study, such as what times of day or year is it most difficult to integrate variable generation, or whether different types of reserves may be necessary than what are already provided.

Estimating the amount of balancing reserves is based on the variability and uncertainty of the net load. If time series data on net load are unavailable, one approach is to estimate the net load (load minus wind minus solar) by estimating the standard deviations of load and wind individually (see figure C.2). It is important to focus on net load rather than on the imbalances of wind and solar generation individually, as load variability and the variability of wind and solar are not correlated. Focusing on the variability of wind and solar alone will overestimate the need and costs for additional reserves.

For load imbalances, one can apply the current amount of reserves needed to manage load imbalances to back out an estimate of the standard deviation of load.

Figure C.2 Statistical Method to Estimate Net Load Imbalances

$$\sigma_N = \sqrt{\sigma_L^2 - \sigma_W^2}$$

Source: Mills 2011.

For example, if 6 percent of peak load is carried as reserves, and it is assumed that this is equivalent to three times the standard deviation to cover 99.7 percent of all probabilities (assuming a normal distribution), then the standard deviation of load imbalances is 2 percent of the peak load.

Wind imbalances can be further broken down into individual components of day-ahead wind forecast errors and the load following and regulation forecast errors from subhourly data if available, and for regulation based on an estimate of 2 megawatts of additional regulation needed for every 100 megawatts of wind projects (see figure C.3).

Ideally, data from the country or region can be applied from day-ahead wind forecast errors and load following and regulation forecast errors from adding wind. If that is not available, day-ahead wind forecast errors from other countries can be used.⁴ For regulation and load forecast errors, a time series of total wind data from projected wind plants would be needed to ensure that the diversity effects of total wind production are incorporated. If those data are unavailable, then existing wind production data can be used with the assumption that it is all uncorrelated, although that may overestimate the smoothing effects of aggregate wind production. If future wind plants are in the area of existing wind plants, then the weighted average of the production of multiple wind plants can be used for planned wind projects. Alternatively, one can scale existing wind production based on a ratio of projected future wind capacity to existing wind capacity, with the assumption that wind power at an existing farm at minute t will occur at a new wind plant τ minutes later (see figure C.4).

Figure C.3 Approximating Wind Imbalances

$$\sigma_W = \sqrt{(\sigma_W^{DA})^2 + (\sigma_W^{FL})^2 + (\sigma_W^{r,f})^2 + (\sigma_W^{r,v})^2}$$

$(\sigma_W^{r,v})^2 = [N * (2 \text{ megawatts})^2]$ where N is the number of 100 megawatts wind plants.

Source: Mills 2011.

Figure C.4 Approximating Wind Profiles for Future Wind Plants

$$Q_{new}(t) = \sum_i w_i \frac{K_{new}}{K_i} Q_i(t - \tau_i)$$

Source: Mills 2011.

Figure C.5 provides a numerical example of the net load imbalance from adding 10,000 megawatts of wind from 100 wind projects, where each plant has 100 megawatts in capacity. The overall load imbalance was determined to be 2,000 megawatts; the net load with additional wind is 2,247 megawatts, meaning 247 megawatts of additional reserves will be necessary in this example.

An even simpler approach is to apply the percentage estimates of additional total reserves necessary for adding wind and/or solar generation from existing integration studies. For example, if 10,000 megawatts of wind capacity is projected to be in operation, and an additional 8 percent of the total capacity of wind is assumed to be needed for additional reserves (regulation and load following), then 800 megawatts of additional reserves is assumed to be needed. A cost of reserve estimate can be applied, such as \$50,000 per megawatts of reserves per year, and multiplied by the 800 megawatts of additional reserves for wind, resulting in a cost of \$40 million per year or \$1.5 per megawatt-hour (Mills 2011). Similar estimates can be derived from integration studies for individual reserves such as regulation and load following.

Clearly, the approximation methods are just that and should not be confused with the advantages of doing an integration study specific to a region or country,

Figure C.5 Numerical Example Using an Approximation Method

Determine net load imbalance with 10,000 MW of wind from 100 plants ($N = 100$)

Standard deviation of day-ahead forecast error (assume 10 percent of total wind nameplate):

$$s_W^{DA} = 10\% \times 10,000 \text{ MW} = 1,000 \text{ MW}$$

Standard deviation of following (assume 20 percent of 100 MW wind plant and all uncorrelated):

$$s_W^{FI} = \sqrt{N} \times 20\% \times 100 \text{ MW} = 200 \text{ MW}$$

Standard deviation of regulation, forecast component (assume 10 percent of 100 MW wind plant and all uncorrelated):

$$s_W^{r,f} = \sqrt{N} \times 10\% \times 100 \text{ MW} = 100 \text{ MW}$$

Standard deviation of regulation, variability component (assume 2 percent of 100 MW wind plant and all uncorrelated):

$$s_W^{r,f} = \sqrt{N} \times 2\% \times 100 \text{ MW} = 50 \text{ MW}$$

Standard deviation of wind imbalance:

$$s_W = \sqrt{(1,000^2 + 200^2 + 100^2 + 50^2)} = 1,026 \text{ MW}$$

Standard deviation of load imbalance (assume 2 percent of 100,000 MW):

$$s_L = 2,000 \text{ MW}$$

Standard deviation of *net load* imbalance:

$$s_N = \sqrt{(2,000^2 + 1,026^2)} = 2,247 \text{ MW}$$

Source: Mills 2011.

Note: MW = megawatts.

as the results from such a study will reflect conditions unique to that region or country (for example, how geographically diversified the wind is, estimates of future load growth, availability of flexible resources, and so on). Nevertheless, approximation methods can be useful when the resources or data for conducting a specific integration study are limited or not available.

Notes

1. For a more comprehensive review of solar power technologies and their cost trends, barriers for deployment, and solutions, see Kulichenko (2011).
2. Deviation management is resolving differences between generation and demand from one intraday market to the next and is comparable to imbalance energy in the United States. Restrictions in real time are defined as limitations due to insufficient secondary and tertiary regulation reserves, insufficient reserve capacity for voltage control, or insufficient reserve capacity for service restoration (REE 2010).
3. This section is based mainly on work by Andrew Mills at the Ernest Orlando Berkeley National Laboratory (Mills 2011).
4. Performance of day-ahead wind forecasts varies from region to region due to wind characteristics, forecasting technology, and degree of geographic diversity in wind plants.

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ISBN 978-0-8213-9734-3

SKU 19734