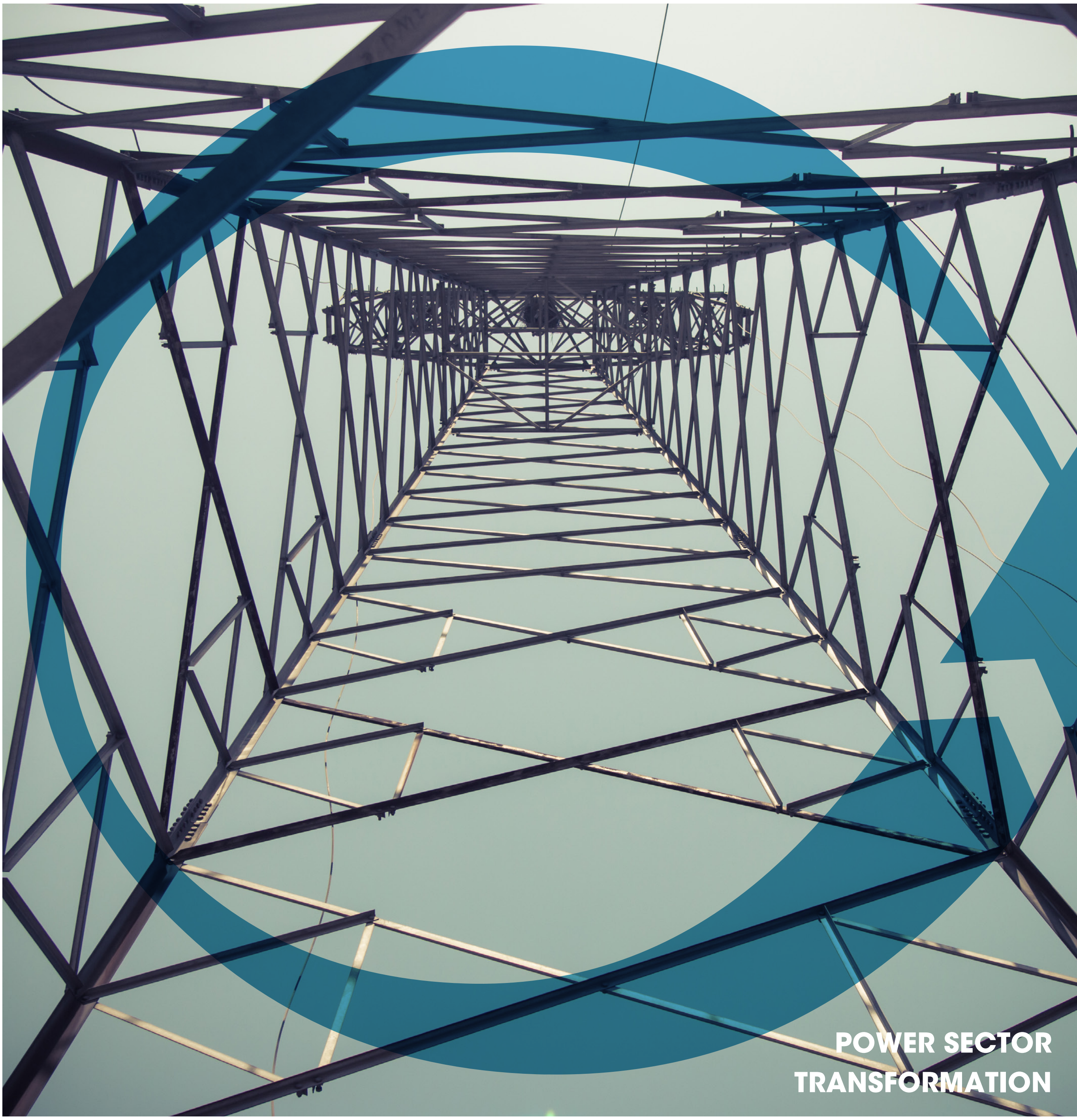
IRENA

International Renewable Energy Agency

THE AGE OF RENEWABLE POWER

DESIGNING NATIONAL ROADMAPS FOR A SUCCESSFUL TRANSFORMATION



About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future, and serves as the principal platform for international co-operation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity.

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CONTENTS

LIST OF FIGURES II

LIST OF TABLES II

LIST OF BOXES III

ABBREVIATIONS IV

EXECUTIVE SUMMARY 2

1. INTRODUCTION 7
   - 1.1 Current status of VRE grid integration 8
   - 1.2 Existing studies on the impact of VRE on power systems 10
   - 1.3 Aim of this roadmap 12

2. STAKEHOLDER ENGAGEMENT 14
   - 2.1 The changing role of existing stakeholders 14
   - 2.2 New stakeholders 17

3. DATA COLLECTION AND ENERGY PLANNING 19
   - 3.1 Renewable energy resource data 19
   - 3.2 Technical and economic data on generation, power flows, and demand 20
   - 3.3 Network and capacity planning and modelling 20
   - 3.4 Grid integration policy data 23

4. ASSESSING CONDITIONS OF FLEXIBILITY 24
   - 4.1 Power generation mix 25
   - 4.2 Grid infrastructure 26
   - 4.3 Institutional frameworks 27

5. ENABLING TECHNOLOGY OPTIONS 28
   - 5.1 Building technological leadership 29
   - 5.2 Developing absorptive capacity 30
   - 5.3 Pilot and demonstration projects 31

6. VRE GRID INTEGRATION MEASURES 33
   - 6.1 VRE grid integration measures for generators 34
   - 6.2 VRE grid integration measures for system operators 41
   - 6.3 VRE grid integration measures for the demand side 44
   - 6.4 VRE grid integration measures for regulators 45
   - 6.5 VRE grid integration measures for technology providers 54

7. RECOMMENDATIONS 56

REFERENCES 58

LIST OF FIGURES

Figure 1: Framework for the development of national roadmaps on renewable energy grid integration....3

Figure 2: Current and future VRE share in annual generation for G20 countries between 2014 and 2030.... 9

Figure 3: The sequence of steps in developing national roadmaps for VRE grid integration....13

Figure 4: Data needs for a national roadmap on renewable energy grid integration 19

Figure 5: Different tools and analyses for energy system planning and design and their interaction....21

Figure 6: Comparison of electricity production and spot prices in Germany between 2011 and 2015....23

Figure 7: Country characteristics that determine the ease of renewable energy grid integration.....24

Figure 8: Overview of technical solutions for VRE grid integration....28

Figure 9: Overview of VRE grid integration measures discussed in international publications 33

Figure 10: Example of different types of grid codes....35

LIST OF TABLES

Table 1: Overview of recent studies on the integration of variable renewable power generation....11

Table 2: Existing stakeholder roles that will require changes for VRE integration....15

Table 3: New stakeholders in the power sector transformation....18

Table 4: Power system properties affecting VRE integration....25

Table 5: Relevance of VRE grid integration measures affecting generators....34

Table 6: Relevance of VRE grid integration measures for system operators 41

Table 7: Relevance of VRE grid integration measures for the demand side....44

Table 8: Relevance of VRE grid integration measures for regulators....48

Table 9: Relevance of VRE grid integration measures for regulators....54

List of Boxes

Box 1: Power sector transformation in Samoa 10

Box 2: Grid investment needs for VRE expansion 22

Box 3: Economic evaluation of smart grid technologies for VRE integration 26

Box 4: Lessons from smart grid demonstration projects for renewable energy integration 32

Box 5: Grid codes – Denmark 36

Box 6: Forecasting – Australia 38

Box 7: Performance reporting – Spain 39

Box 8: Grid connection and access – Turkey 40

Box 9: Congestion management – New Zealand 43

Box 10: New tariff structures – Vanuatu 46

Box 11: Demand side management – Republic of Korea 47

Box 12: Market based renewable energy dispatch – Germany 50

Box 13: Capacity market – Colombia 51

Box 14: Market integration and cooperation – Gulf Cooperation Council 52

Box 15: Data ownership rights – California, US 53

Box 16: Communication protocols – Japan 55

ABBREVIATIONS

AC	alternating current
AMI	advanced metering infrastructure
CEM	Clean Energy Ministerial
CHP	combined heat power
CSP	concentrated solar power plants
DC	direct current
DSM	demand side management
DSO	distribution system operator
EV	electric vehicle
ENTSO-E	European Network of Transmission System Operators for Electricity
EUR	euro
FACTS	flexible AC transmission system
G7	Group of 7
G20	Group of Twenty
GIVAR	Grid integration of Variable Renewables
GW	gigawatt
Hz	hertz
HV	high voltage
ICT	information and communication technology
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IGCC	International Grid Control Cooperation
IPCC	International Panel on Climate Change
IRENA	International Renewable Energy Agency
kWh	kilowatt-hour
kWp	kilowatt-peak
NGO	non-governmental organisation
NREL	National Renewable Energy Laboratory
O&M	operation and maintenance
PV	photovoltaics
R&D	research and development
SCADA	supervisory control and data acquisition
SID	Small Islands Developing States
TSO	transmission system operator
VRE	variable renewable energy
US	United States
USD	US dollars

EXECUTIVE SUMMARY

Renewable power generation capacity accounted for 1,828 gigawatts (GW) in 2014, compared to around 1,500 GW of gas-fired power station and 1,880 GW of coal-fired power station globally. The majority of power generation comes from hydropower (1,172 GW), followed by wind power (370 GW), and solar photovoltaics (175 GW). In particular, the share of variable renewable energy from solar photovoltaics and wind power is expected to increase from 3% of annual generation production in 2014 to around 20% by 2030. This development will have profound impacts on how our power systems are operated, managed, financed and governed.

Most countries are in the very early stages and only a few have reached levels where variable renewable energy have an impact on the way that power systems have been operated and managed traditionally. However, the power sector is changing fast. In an industry where classical investment times are thought of in decades rather than years, solar photovoltaic costs alone have fallen nearly 80% since 2008: a speed of change comparable to that seen in the information technology revolution. This means that all countries need to evaluate the implications of these changes on their current practices.

Policy makers will play an enabling role in a transition towards renewable power generation. They need to start to engage in this transition, even if the share of variable renewable energy is still very low. They also need to take a holistic approach and long-term perspective. This means that the power sector transformation should focus on a transition of the system as a whole, and not treat the integration of renewable power generation as a separate issue. Demand side management to support system flexibility, energy efficiency policies to reduce investments in transmission and distribution networks, smart meters to support consumer choice, and smart grid technologies to reduce the costs of asset management, are examples of policies that increase the reliability, affordability and security of power systems, whilst simultaneously supporting the integration of renewable power generation.

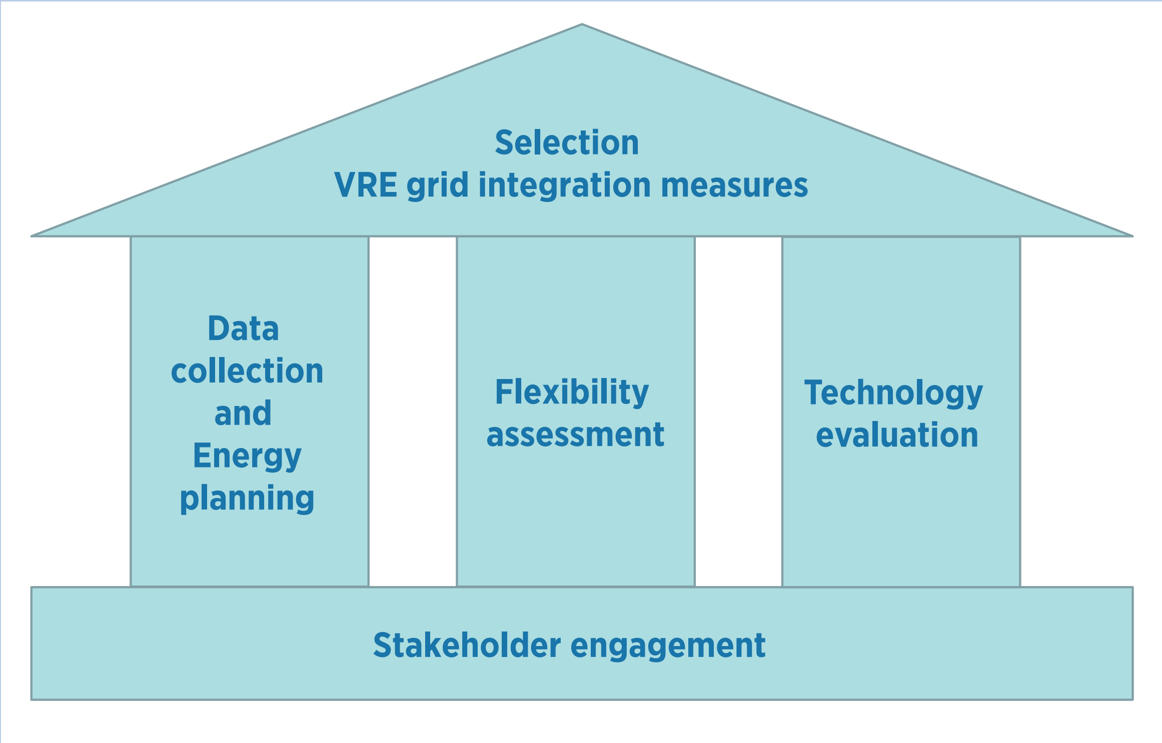
Furthermore, the power sector transformation will occur in stages with different implications along the way. Policy makers need to ensure that institutional frameworks governing the grid infrastructure are based on a long-term vision, and can be adapted as we learn what works and what does not. The same applies for the principles or market designs that govern how generators manage their portfolio of generation technologies. New relationships between electricity suppliers and consumers producing their own electricity need to be defined. New business models need to be created that allow system operators to raise the finances needed to build the 21st century grid.

This report focuses on the role that national policy makers will play in this transformation process. The main challenge being that there is not a single roadmap or technology that provides the solution. Each country situation is unique, and local solutions need to be found to support the transition towards a renewables-based power system. It is therefore very important that policy makers work together with generators, local system operators and electricity suppliers to collectively design the future.

Worldwide, countries are planning national roadmaps to support power system transformations.[1] The report provides a framework for the development of such roadmaps (see Figure 1). The framework focuses on the process that determines the relevant grid integration measures, how this choice depends on the local

1 Joint statement of the endorsing Clean Energy Ministerial (CEM) countries of Denmark, Finland, France, Germany, India, Indonesia, Japan, Korea, Mexico, Norway, South Africa, Sweden, the United Arab Emirates, the United States, and the Directorate-General for Energy of the European Commission in May 2015 (CEM, 2015).

Figure 1: Framework for the development of national roadmaps on renewable energy grid integration



Where VRE: variable renewable energy

conditions within the specific country, and how to ensure that all stakeholders involved are aligned, turning ambitious targets into a reality.

The foundation for the development of a national roadmap is stakeholder engagement. Subsequently, policy makers need to put three pillars in place to support the selection of relevant grid integration measures for variable renewable energy: data collection and energy planning; flexibility assessment; and technology evaluation. The key insights for this framework are:

The power sector transformation will attract new stakeholders, and will change the role of existing stakeholders. The national roadmap should engage all stakeholders from the start.

In most countries, utilities have been a central stakeholder to provide reliable, affordable and secure electricity. In a transition towards a renewables-based power system, the function and technical capabilities of utilities and the institutional features governing the grid need to be revisited. Transmission and distribution system operators and energy planners will need to develop or update their procedures to deal with supply-side variability, regulators will need to consider the possibility of new entrants and a more pro-active role of consumers, and distribution system operators will have to become more active in managing reverse flows, providing additional system services, and controlling load locally due to distributed generation. The need for more distributed control systems will also introduce a new information paradigm, with impacts on data processing capabilities, data sharing agreements, privacy laws, communication protocols, and data security measures.

Variable renewable energy will also change the remuneration and compensation schemes for generators and system operators. This transformation will attract new stakeholder groups, such as distributed generators, prosumers, aggregators, new finance institutions, the consumer service and the car manufacturing industry.

A national roadmap, therefore, needs to identify the impacts of variable renewable energy on existing utilities, and also identify the new stakeholders that will be entering the power sector. Both sets of stakeholders will need to be engaged from an early stage, because they will be crucial to the successful implementation of the grid integration measures.

A national roadmap should be supported by processes to collect data on renewable energy resources, generation, power flows and demand profiles, and an institutional process for long-term planning of generation capacity and networks.

The integration of variable renewable energy will require a systems approach, which means that all elements of the power system will need to be adjusted and adapted. Detailed information about the current and future state of the power sector is key for such an approach. Key processes for collecting data and energy planning are:

- Detailed data on renewable energy resources, including geographical distribution, land use restrictions and accessibility of renewable energy resources;
- More detailed real-time information on the generation profiles, power flows, and electricity demand, which allows system operators to adapt their procedures to deal with the increased variability and uncertainty on the supply side, make more effective use of demand-side management, and evaluate the technical impacts of variable renewable energy on the grid.
- Power system modelling to assess different technological options for the generation mix and network topography, including the potential of micro-grids, energy storage and interregional balancing of supply and demand;

Finally, data collection should be an iterative process that ultimately results in more effective and efficient grid integration policies. This iterative process will require easily accessible databases that can be used for inter-country learning and to share experiences.

The selection of grid integration measures should start with an analysis of the existing flexibility options within the current power sector.

The share of variable renewable energy in the power generation mix is an important indicator of the need for different grid integration measures. However, system characteristics like the power generation mix, the status of the grid infrastructure, and the institutional frameworks in place, also affect when and what grid integration measures will be relevant. Institutional frameworks includes regulatory structure, the wholesale and retail market structure, and schemes to recuperate grid investment needs. Furthermore, interconnections between neighbouring countries will become increasingly important to ensure sufficient flexibility within the system.

A national roadmap should start with an analysis of existing flexibility options. For example, the technology, age and design of the stock of dispatchable power generation will determine the flexibility of dispatch and operating reserves. Similarly, the technological maturity and competitiveness of variable renewable energy technologies available will dictate the role that variable renewable energy can play in providing services such as frequency and voltage regulation, and load following.

The status of the grid is also an important determinant in the selection of grid integration measures. A strong and well-connected power grid ensures that the demand can be met at all times, that dispatch of the most economic resources can be guaranteed, and that the flexible resources in the system can be used in the most efficient way. Consequently, grids should be upgraded and optimised in parallel or even ahead of increasing the share of renewables, rather than waiting for infrastructural issues to become an obstacle. Countries with developing grid infrastructures have more options to integrate variable renewable energy into a grid expansion plan, using them to support grid access, or strategically locate them to increase reliability and remove transmission bottlenecks.

Technology solutions to support the integration of variable renewable energy are available, but efforts are required to understand their implications within the national context.

There are a large number of technologies available to support the integration of variable renewable energy in the power sector, ranging from smart inverters to forecasting techniques to distributed automation. Most technologies are already commercially available, although there are still rapid developments taking place. For example, battery storage systems have come down in costs by around 50% in the last couple of years and could become an economically viable option to support self-consumption of rooftop solar PV in areas with high residential prices if cost reductions continue. The rapid developments in performance and costs will also affect the relevance of grid integration measures within their national context.

Consequently, a national roadmap should not only consider how these technological options can facilitate grid integration measures, but also how national capabilities can be created to develop, adopt and test the impacts of these technologies. Pilot and demonstration projects are an intrinsic part of a national strategy for the power sector transformation.

The selection of appropriate grid integration measures will be an iterative process, in which the choice of one measure will impact the pre-conditions for the next iteration.

This report has identified 20 grid integration measures to support variable renewable energy. For each measure, this report describes:

- At what share of variable renewable energy is the measure relevant?
- Which stakeholders need to be involved in the implementation process?
- What data collection processes are needed to support the measure?
- Under what flexibility conditions is the measure relevant?
- What technologies are needed to support the measure?

The selection of grid integration measures will depend on the preconditions in place and the support of the stakeholders involved. Another important consideration is how different measures are sequenced such that they support and re-enforce each other as the system evolves.

Countries across the globe already have hands-on experience with the practical implementation of these measures. International cooperation between policy makers and other stakeholders will be an important tool to ensure continued learning and the exchange of best practices.

National governments need to play a leadership role in the power sector transformation, because it has far reaching impacts.

Evidence from around the world suggests that the technical challenges of integrating variable renewable power generation faced by most countries leading up to 2030 can be met, and that utilities have the technical solutions available to continue to ensure reliable, clean and affordable power. However, renewable power generation also has far reaching consequences for: the economics of power generation; economic growth for and inclusion of local communities and cities; the engagement of individual consumers in the power sector; and national policies on energy security and climate change. In other words, the integration of variable renewable power generation ultimately has societal consequences and warrants leadership from policy makers.

Policy makers need to anticipate the far-reaching implications of a power sector transformation and act pro-actively to translate renewable energy targets into palpable actions on the ground. However, they cannot manage this transition alone. Technical expertise and financial resources are required, data needs to be collected and analysed, the utilities need to be incentivised to implement the appropriate technical and operational measures, and international cooperation is required for interconnectors and the exchange of best practices. The development of a national roadmap for the integration of variable renewables is a key step to guide this process, ensuring that the selected measures are relevant for local conditions, and aligning actions across stakeholders and countries.

1. INTRODUCTION

In its institutional publication, REthinking Energy, IRENA examined the increasing role of renewable energy in the power sector transformation. It has found that, world-wide, well over 100 gigawatt (GW) of new renewable capacity has been added every year since 2011 (IRENA, 2014a). This means that the newly installed capacity of renewable power generation is greater than that of fossil and nuclear power combined. As a result of these additions, by 2014, the share of renewables in total electricity production exceeded a record 22%, of which 16.4% was hydro and 3.6% was solar photovoltaic (PV) and wind. The total installed capacity of the different renewable power generation technologies together is larger than that of nuclear power stations, gas-fired power stations and on par with coal-fired power stations.

There are two distinct categories of renewable power generators: dispatchable and variable (IRENA, 2015a). Dispatchable renewable power generators control their output within a specific range, just like conventional fossil power plants. Reservoir hydropower plants,[2] biomass (including biogas) power plants, geothermal power plants, and concentrated solar power (CSP) plants with thermal storage (such as molten salt) are all dispatchable plants. Integrating these renewable sources into power systems does not pose additional challenges. In fact, many power systems already achieve high electricity shares from dispatchable renewable power stations, particularly hydropower and geothermal power (*e.g.* in 2013: Austria 72%; Canada 61%; Brazil 80%; Colombia 79%; Iceland 100%; New Zealand 69%; and Norway 96%).

Variable renewable energy (VRE) has a number of characteristics that are different from conventional power sources and the process of grid integration is therefore different. Furthermore, VRE is changing the operations of existing assets, which means that due to their rapid growth management practices across the power sector are changing. The VRE characteristics that drive these changes are (IRENA/IEA-ETSAP, 2015; IRENA, 2015a):

1. VRE only produces electricity when resources are available, which means that VRE sources are less able to be relied upon during peak demand times (VRE have a low, so-called, capacity credit). A strategic mix of renewable energy sources at different locations can significantly reduce the impact of variability.
2. The forecasted VRE generation can differ from actual production, because of unexpected changes in resource availability that requires additional needs to balance supply and demand at short notice (from tens of seconds to hours). Improved forecasting techniques and shorter dispatch intervals have decreased these effects, yet some unpredictability remains. There are a number of conventional techniques available to support short-term balancing (Milligan, Kirby, and Beuning, 2010; Holttinen, *et al.*, 2011).
3. Like all natural resources, the quality of VRE resources is location-specific. Consequently, trade-offs exist between the location of the generator, the quality of the resource, and associated costs for transmission and distribution lines.
4. VRE technologies are modular, and they generally reach efficient scale at much smaller sizes than most conventional generating sources. Consequently, they are relatively easy and quick to install and can be used to produce electricity locally.
5. Most VRE technologies are connected to the grid via power electronics and as a result do not automatically support grid stabilisation. In the case of high shares of VRE, new regulation will need to be introduced to ensure that power electronics provide additional support to stabilise the grid.
6. The production costs of VRE power generation are largely determined by the up-front capital costs, because the resources to produce electricity (sun and wind) are for free. Consequently, the marginal costs for producing a unit of electricity from a VRE source is lower than the marginal

2 Most reservoir hydropower plants are variable at longer time scales, say over a few years. This is especially true if the impoundment capacity is limited, so that they cannot store all of the energy available in a wet year to make up for the lack of energy in a dry year.

costs for conventional power plants. In power systems with wholesale markets, this will change the price dynamics especially in periods with high or low availability of VRE power generation (Sensfuss, Ragwitz and Genoese, 2007; Clo, Cataldi and Zoppoli, 2015)

These characteristics have an impact on the way that VRE is integrated into the existing grid, and at the same time transform the power system as a whole. In this context, "grid integration" involves the incorporation of a generator into a power system and is a process required for all generation technologies. The process includes connection to the grid and optimal transmission of the generated power, either for end-use or to be stored for later use. This has to be achieved while maintaining acceptable levels of quality and security of supply and ensuring affordability and accessibility for the consumers. Power system transformation is "the active process of creating the policy environments that promote investment in – and innovation towards – secure, smart, affordable, clean and reliable power systems" (C21, 2015)

Looking ahead, the results of IRENA's global renewable energy roadmap suggest that national renewable energy plans would result in an increase of the global annual renewable power generation share from 22% in 2014 to 27% by 2030 (IRENA, 2014b). However, the results also suggest that existing plans – especially for variable renewable energy sources like solar PV and wind power – are underestimating the current market growth. Consequently, the results of REmap 2030 show that there is the option to deploy an additional 800 GW of solar PV and 550 GW of wind between 2010 and 2030.

If countries deploy these additional options, the share of renewables in the power sector would increase to more than 40% by 2030. The share of VRE would increase from 3% of total power generation in 2014 to around 20% in 2030. Additionally, more than one-third of the solar PV deployment could be achieved in a distributed manner in residential and commercial sectors, including rural electrification.

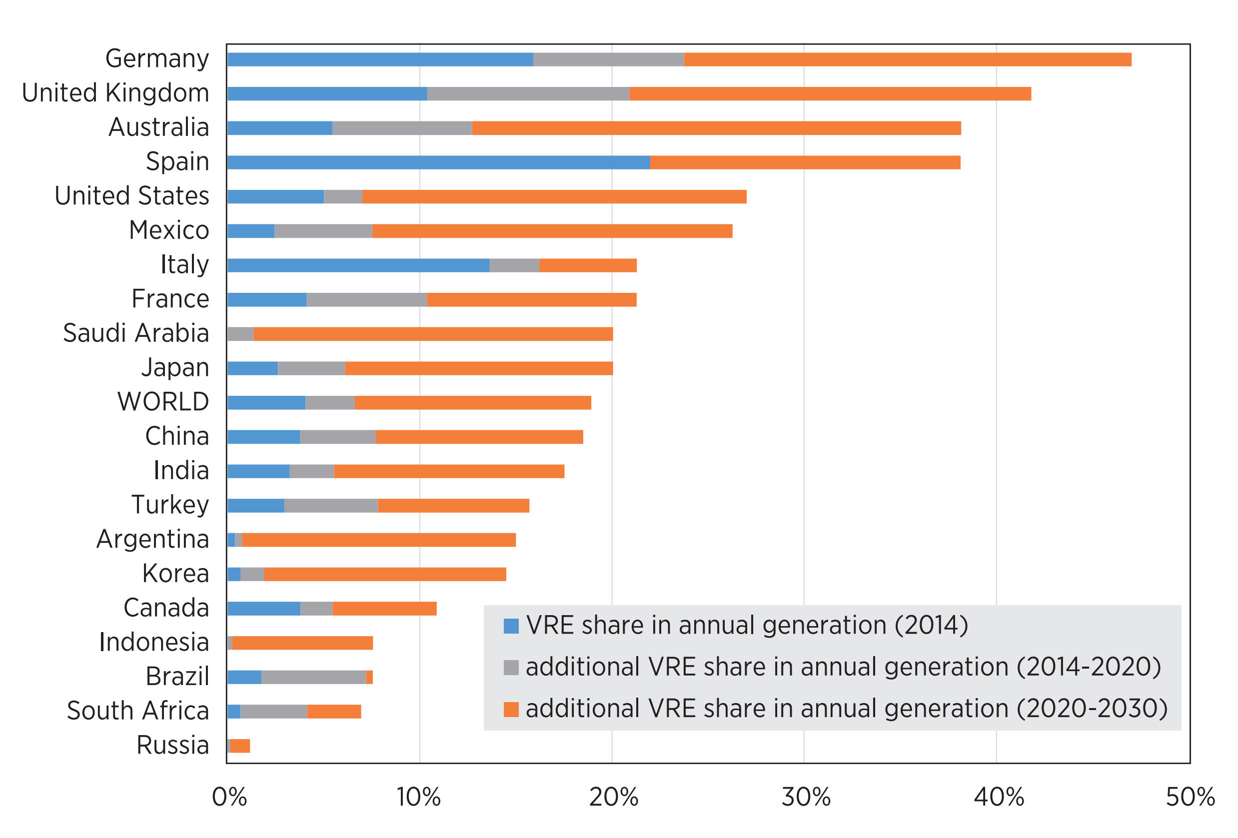
The rapid growth of VRE will not only impact grid integration policies, but also impact the operation of existing assets, the efficiency and effectiveness of power markets, the stakeholders' engagement in the power sector, and the role of regulators. As the share of VRE continues to grow, the structure of the industry and the nature and role of power producers and distributors are undergoing changes at multiple levels. Existing business models are now at the centre of policy discussion across many countries, as they have to be adapted to integrate new players, such as solar PV leasing companies into the market. Attracting investments in grid infrastructure is increasingly becoming a priority; in some instances, to upgrade the ailing or outdated infrastructure, whereas in others, to meet growing energy needs and expand energy access. Regulators need to revisit the principles they have been using to ensure reliable and affordable power supply. In the midst of these developments, it is the task of the policy makers to guide this transformation process towards economic, social and environmental welfare.

1.1 Current status of VRE grid integration

Despite the rapid growth of VRE, only a small number of countries are managing grid systems with 15% or more of annual power consumption produced by VRE.[3] These countries – which include Denmark, Germany, Ireland, Italy, Portugal, and Spain – provide valuable lessons on how the grid infrastructure or the processing for controlling and managing the grid can be adopted to accommodate these shares. For example, Denmark, which produced 41% of electricity consumption from wind power in the first half of 2014, has relied on several measures to integrate such a high share wind power into its power system. These include VRE-related grid codes, grid planning, robust interconnections, accurate forecasts, adequate reserve capacity, increased operational flexibility, frequently updated operational schedules, well-functioning electricity markets and demand management (DEA, 2010; Energinet, 2014). Similarly, Germany produced around 15% of its electricity from wind and solar power in 2014. Instantaneous penetration rates reached more than 75% in August

3 There are multiple ways to calculate the share of VRE. In REmap 2030, the share is calculated based on the annual electricity production from VRE, divided by the annual electricity consumption within the country (both measure in watt-hours). This indicator ignores VRE generation exported to neighbouring countries. Another way to measure the VRE share is the ratio of peak VRE power to peak load (both measured in watts) (IRENA, 2013). In general, the former indicator results in a lower share than the latter.

Figure 2: Current and future VRE share in annual generation for G20 countries between 2014 and 2030



Note: 2014 is based on the latest statistical information available, 2020 data is based on IEA's medium term renewable energy market report, and 2030 is based on IRENA's REmap 2030 results of renewable power potential.

Sources: IEA, 2014a; IRENA, 2014b; GlobalData, 2015a; GWEC, 2015

2015.[4] Germany has ambitious renewable energy targets and is expected to reach VRE shares of 38%-49% by 2030 (EWI, GWS, Prognos, 2014; BMUB, 2015). It has taken steps to encourage renewable power production in response to demand to increase investments in flexible power generation and storage, and to accelerate grid expansion. Several studies have highlighted the need for additional measures (BDEW, 2013; DENA, 2010; Schroeder *et al.*, 2013; BMWi, 2015) to achieve future renewable energy targets.

Figure 2 shows an overview of the renewable energy plans for the G20 countries, which account for 80% of global power generation, as well as the world's average. In 2030, it is expected that the world's share of power generation from VRE will reach levels that are similar to the shares already experienced in countries like Germany, Ireland, and Spain. Only a limited number of countries will increase their share of VRE power generation to above 30% as experienced in Denmark.

In the longer term, there are a large number of smaller countries and states that have ambitious targets for VRE. Denmark, Ireland, and Portugal are examples of countries in Europe, the states of California, Texas, and Vermont are examples in the US. Furthermore, many islands and Small Island Developing States (SIDS) are in the process or have ambitious plans to transition their diesel-based power systems to a combination of wind and solar energy. Like the isolated power systems of Ireland and Texas, islands have particular challenges that must be overcome to maintain high levels of service reliability. For example, the Spanish island El Hierro is transitioning towards renewable power generation, and

4 This percentage is calculated based on the instant penetration rate of solar PV (24 GW) and wind power (18 GW) divided by national electricity demand (55 GW).

Box 1: Power sector transformation in Samoa

IRENA's grid stability assessment for Samoa

Samoa has a national target to generate 100% of the island's electricity supply from renewable energy by 2017. The target is supposed to be achieved through a combination of solar PV, wind power, and hydro power. To achieve this target, Samoa's utility Electric Power Corporation (EPC) has already installed 7 MW of hydro power, signed power purchase agreements for 11 MW of solar PV, and intends to increase its existing 500 kW wind power generation capacity. Samoa's peak demand is around 20 MW.

IRENA's grid stability study found that despite ambitious plans, a high dependence on diesel generators would remain if no extensions are made to the current grid infrastructure. However, with voltage control and battery storage systems up to 96% of the island's electricity demand could be met by renewable energy (IRENA, 2015i).

as a first step, turned off their diesel generators to run their power system on a combination of hydro, wind and solar PV for a couple of hours. Due to the smaller size of the power systems on many of these island states, the share of VRE can rapidly increase over a short period of time.

The share of VRE in annual electricity production is only a rough indicator for their impacts on the power sector. A more detailed view of each country's situation in terms of its existing infrastructure, institutional structure, grid integration policies and research, development, deployment and demonstration activities can be developed to obtain a more complete understanding of the status quo. As will be seen in the following chapters, it is essential to identify the priority areas for recommendations for the roadmap. As such, the measures and recommendations are not only dependent on the share of VRE, but also time and situation dependent.

Besides an understanding of the context, it is important to stay abreast of the status and developments of available technological options that support the integration of VRE. For example, VRE technology providers are continuously improving the structural, mechanical and electrical designs of solar PV and wind power to ensure that they can provide certain grid support services (REserviceS, 2014). Furthermore, countries like Germany have dedicated research funding to support their energy transition, including dedicated programmes on energy storage and power grids (BMWi, 2014)

1.2 Existing studies on the impact of VRE on power systems

The attention for the potential impacts of VRE on power systems has increased very rapidly in the last five years, even though only a small number of countries have significant levels of deployment. These growing concerns are the result of three developments:

- The costs of renewable power generation have decreased more rapidly than most analysts expected, which means that deployment levels (albeit low in percentage terms) are higher than anticipated in most forecasts;
- The political profile of renewable energy has significantly increased, and many countries have raised their national targets for renewable energy accordingly (IRENA, 2015b);
- Most utilities are still unfamiliar with deploying renewable power, so they have been questioning the practical implications of policy maker's plans on renewable energy.

At a political level, the Clean Energy Ministerial (CEM) – established in 2010 – was one of the first international fora where this topic was explicitly discussed.[5] At the same time, a number of countries were already examining and adapting their practices and policies

5 The CEM has established the 21st Century Power Partnership as a platform to develop public/private collaboration in the area of power sector transformation. See: www.21stcenturypower.org

to integrate variable renewable energy (Morales, *et al*., 2008; Holttinen, *et al*., 2009; Kröger-Vodde, 2009; Milligan, Kirby, and Beuning, 2010; Dudurych, 2010; EnerNex Corporation, 2011).

Also, a number of international organisations have examined the issue of renewable energy grid integration in more detail. The International Panel on Climate Change (IPCC) dedicated a separate chapter to the issue of

Table 1: Overview of recent studies on the integration of variable renewable power generation

Institution and title	Content
IEA – RETD – Integration of Variable Renewables (IEA-RETD, 2015)	Analysis of 9 case studies recommending eight activities to support integration of variable renewables
World Bank – Bringing Variable Renewable Energy up to Scale (World Bank, 2015)	Overview of different measures for VRE integration with specific focus on policy and regulatory options to support gas-fired power stations and energy storage as flexibility measures.
Lawrence E. Jones – Renewable Energy Integration (Jones, Renewable Energy integration. Practical management of variability, uncertainty, and flexibility in power grids, 2014)	Practical management lessons to deal with variability, uncertainty, and flexibility in power grids with case study analyses from Africa, Germany, India, different Island States, Scandinavia, and several states in the US.
IEA-ISGAN – The Role of Smart Grids for Integrating Renewable Energy (IEA-ISGAN, 2015)	Case studies of smart grid technologies for renewable energy grid integration in Austria, Canada, Korea, Sweden and the US.
Agora Energiewende – The European Power System in 2030: Flexibility Challenges and Integration Benefits (Agora Energiewende, 2015)	Assessment of geographical smoothing effects, cross-border exchange, and flexibility needs for VRE growth. Case studies for Austria, Belgium, France, Germany, Luxemburg, Netherlands, and Switzerland.
EPRI – The Integrated Grid (EPRI, 2014)	Identification of 4 key areas of action for integrating distributed energy resources in the grid.
IEA – Grid Integration of Variable Renewables (GIVAR) project (IEA, 2014b)	Provides an economic analysis of flexibility, recognises and categorises country-specific measures; and provide recommendations for system-friendly VRE deployment, improved system operation and additional flexibility resources.
World Bank – Operating and Planning Electricity Grids with Variable Renewable Generation (World Bank, 2013)	Challenges, state of the art practices and lessons from literature and case studies for integration of VRE.
NREL – Integrating Variable Renewable Energy in Electric Power Markets (NREL, 2012a)	5 Best Practices to integrate VRE.
IEA-ISGAN – Smart Grid Contributions to Variable Renewable Resource Integration (IEA-ISGAN, 2012)	Relationship between smart grid technologies and VRE challenges. Featuring case studies from ISGAN member nations
NREL – Renewable Electricity Futures Study (NREL, 2012b)	Scenario analysis for resource adequacy for high shares of renewable power generation in US power sector
ECF – Roadmap for a decarbonised power sector (ECF, 2012)	Scenario analysis to assess grid investment needs, demand response, energy efficiency measures and overall system costs of decarbonising the European power system
MIT – The Future of the Electric Grid (MIT, 2011)	Challenges, opportunities and recommendations for increased efficiency, reliability for VRE integration in the US
NERC – Accommodating High Levels of Variable Generation (NERC, 2009)	Identifies key areas for study, coordination, and consideration to integrate VRE in North America

renewable energy grid integration (Sims, *et al.*, 2011), and the International Energy Agency (IEA) concluded their three-year study on Grid Integration of Variable Renewables (GIVAR) in 2014 (IEA, 2011; IEA, 2014b). The latter report examined seven case studies covering 15 countries where variable renewable power generation is growing rapidly, supplemented with technical and economic analysis of future. Many of the case studies stem from regions – countries or states – that are at the forefront of renewables deployment, such as Denmark, Germany, Ireland, and Spain in the EU; Alberta, Hawaii, Texas in Northern America; and India and Japan in Asia. The World Bank published a report with lessons from real-world case studies (Denmark, Germany, Portugal and Spain) in 2013 (World Bank, 2013).

Mostly, these studies provide three analytical insights:

1. There is a large range of grid integration measures available to support VRE;
2. The relevant measures highly depend on a number of local specific conditions as outlined in the different case studies;
3. Each measure requires different stakeholders to take action and/or get involved.

This report builds upon the lessons from existing studies, and places them into a framework for the development of national roadmaps on the integration of renewable energy in the power sector.

1.3 Aim of this roadmap

While there is a widespread agreement that the share of renewables for power generation will continue to rise, the future electricity system design is still not evident. In the past few years, IRENA has analysed VRE deployment options across the world, and the technologies, policies and regulatory frameworks required for the integration of renewables into electricity grids. It has also provided specific technical methodologies and tools to assess the grid infrastructure to enable the integration of renewables into electricity grids.

Analysis of the country situations makes it abundantly clear that different countries, and in many cases different regions within a country, have distinct characteristics with respect to the integration of VRE into its power system. The wide variation in policies, market structures, power systems, geography and national targets means that there is no one-size-fits-all approach that can be used to formulate a global roadmap with a definite timeline. This prompts a departure from a conventional roadmap, which proposes definite steps or "best practices" that can be universally applied along a proposed timeline. While it is true that an approach taking context-specific factors into consideration may be less directive in nature, the intent of this report is to assist in creating conditions in which better-informed decisions can be made more easily, keeping in mind the context in which they are made and the goals they are meant to achieve.

Furthermore, this report explicitly aims to support national policy makers. As such, the report does not provide the technical details provided by some of the report listed previously, but rather focuses on the process required to make informed decisions. Therefore, the question that we address in this report is:

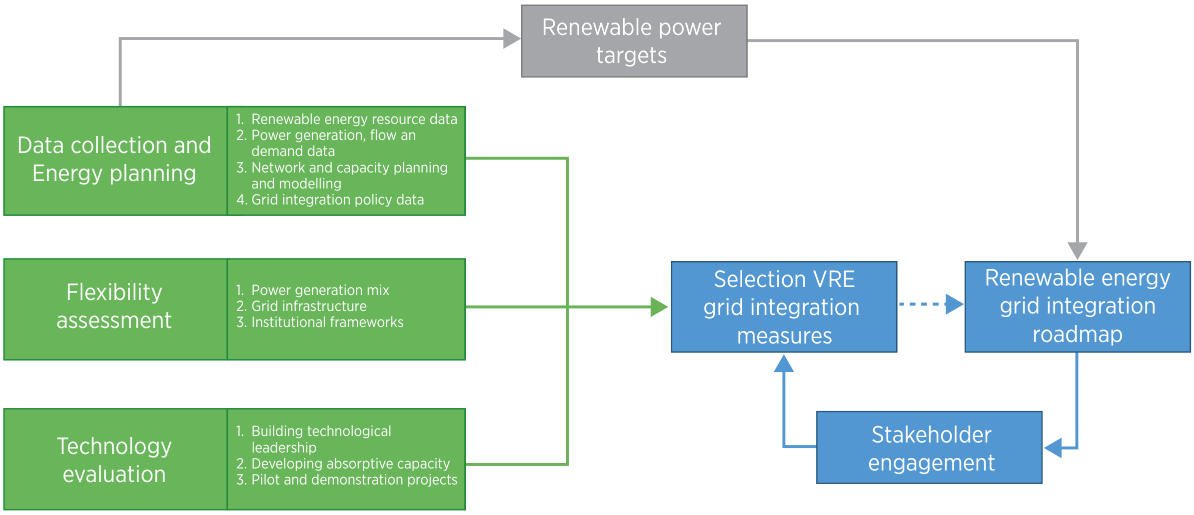
What are the relevant actions that policy makers need to consider for the development of a national roadmap on the integration of variable renewable power generation?

The proposed framework for the development of a national roadmap is illustrated in Figure 3. The framework focuses on the steps after a renewable power target is set or being considered. This includes:

Step 1: Stakeholder engagement
Step 2A: Collect data and support energy planning
Step 2B: Assess the flexibility conditions
Step 2C: Identify and evaluate the relevant technologies
Step 3: Select the appropriate VRE grid integration measures

Each step will be explained in more detail in the next chapters. **Chapter 2** discusses how to determine the relevant stakeholders by identifying their changing or new roles in the power sector transformation. **Chapter 3-5** identify the different analytical steps required for an assessment of VRE grid integration measures. **Chapter 3** discusses the data and associated institutional/political structures needed for data collection and energy planning. This is intended to create an environment in which informed decisions about policy formulation, project implementation and investment can be made. **Chapter 4** discusses how to assess the flexibility conditions as determined by the power system

Figure 3: The sequence of steps in developing national roadmaps for VRE grid integration



characteristics, existing capabilities and potential, and the institutional frameworks governing the power sector. **Chapter 5** discusses the need for good knowledge of technologies, including their applicability, performance, barriers to implementation and technological maturity. **Chapter 6** provides an overview of different grid integration measures in terms of the stakeholders involved and the conditions under which they are relevant (data, flexibility, technology). **Chapter 7** concludes this report with a number of recommendations.

2. STAKEHOLDER ENGAGEMENT

In most countries, utilities have been a central stakeholder to provide reliable, affordable and secure electricity. VRE will change the technical capabilities required from utilities, and their role in operating the grid. At the same time, VRE is attracting new stakeholders into the mix. This chapter provides an overview of how these stakeholders are affected.

In most cases, power systems have traditionally evolved to take electricity from large, centralised power stations through transmission and distribution lines to the consumer. Utilities play a central role in power systems providing functions as generators, system operators, and suppliers of electricity. Generators produce electricity and feed it into a grid. System operators[6] have to balance the variation in demand by providing protocols to schedule the electricity production from power plants. They are aided in this by extensive experience and statistics on electricity consumption, making it predictable to a large extent. Electricity suppliers provide the electricity to the consumer, and are also responsible for the metering and billing process. The role of regulators has traditionally been to ensure that utilities do not take advantage of the natural monopoly that power systems provide, while at the same time ensuring that sufficient funds are available to invest in new capacity, and maintain and operate the grid. Except for large industrial users, consumers had a passive role in this system.

Variable renewable energy is changing this paradigm. The development of a national roadmap to integrate variable renewables starts with the question what will their impact be on the existing stakeholders in the power system, and what new stakeholders will need to be involved. VRE is also accelerating technology development in other areas, such as smart grids and storage, bringing new stakeholders into that part of the process (IEA, 2015).

While the stakeholders will act as the agents for change, it is also important to consider the effect of these changes on them. A national roadmap should recognise the impacts of VRE on these stakeholders, and engage them in the development of the roadmap itself.

6 System operators can be independent from the grid operators, with the latter owning the grid infrastructure itself.

2.1 The changing role of existing stakeholders

Incorporation of VRE generation into the existing power system raises a number of technical challenges related to grid operations, but also non-technical issues related to data ownership rights, grid security, technological standards, etc. (IRENA, 2013). These challenges affect generators, system operators, technology providers, regulators, energy planners, and the general public.

An important role of system operators is to balance supply and demand at all times, and ensure frequency remains within predetermined bandwidths (mostly around 50 hertz or 60 hertz). With the introduction of VRE, system operators may require additional measures to maintain stability and reliability of the system as the share of VRE increases.

Dealing with variable power flows is not new for power system operators, and in general variability in demand is larger than the expected variability in supply due to VRE. The traditional model employed to ensure access to affordable power in a reliable way has been to cover the base load using base load plants, which have low variable costs running at full capacity. The peak load is supplied by 'peaking power plants', having higher running costs, but being able to ramp up and down to match demand, which can be predicted in advance based on past trends and experience. In between base-load and peak, flexible load following plants are used to meet demand as it fluctuates during the day. Some reserve capacity is maintained above the peak demand level to deal with plant failures and extreme demand levels.

VRE generators are increasingly replacing baseload and load following power plants in the generation mix. At low VRE shares, VRE is often competing with load following plants like flexible gas-fired power stations.

Table 2: Existing stakeholder roles that will require changes for VRE integration

Existing stakeholders	Relevant activities for VRE integration
Generators	System services and support; Harmonics; Forecasting
Transmission system operators	Manage supply side variability; System monitoring; Provide system inertia; Cooperation between neighboring networks
Distribution system operators	Power dispatching; Local load control; Fault handling; Safety procedures for unintentional islanding
Technology providers	Communication protocols; Data handling
Policy makers	Renewable energy targets; Renewable energy support policies; Mandates on interconnection, grid connection, market design and grid codes
Regulators	Definition of grid connection policies; Grid codes; Market design; Compensation schemes; Support flexibility
Energy planners	New transmission network topologies; Locationspecific planning; Adequacy
Certification bodies	VRE standards and grid codes; Certification
General public	Public engagement in power sector transformation
NGOs	Economic, environmental and social assessments of power sector transformation

As the share of VRE increases, baseload power will become increasingly irrelevant (IRENA, 2015a) and the complementarity between VRE and load following plants becomes more important.

System operators need to anticipate these changes, and new capabilities will have to be developed to implement methods for controlling and regulating the power system to ensure reliable supply of power. Solutions such as upward and downward regulation of power generation, power trading and demand side management will become increasingly important sources of flexibility.

Transmission system operators (TSO) will need to develop their capabilities to increase responsiveness to deal with increased variability on the supply side based on forecasts and real-time data. System operators will need to monitor grid characteristics and requirements of the power to help make informed decisions regarding specification of grid codes, evaluation of technological options in the long term and identification of congested transmission lines and need for curtailment in the short term. Greater coordination and cooperation between neighbouring TSOs to maintain balance of power flows through power trade, and integrated planning could emerge as a key strategy in many cases. For example, the International Grid Control Cooperation (IGCC) is a collaboration of TSOs in different European countries, working together to reduce the need for control power.[7]

Due to an increase in distributed generation, distribution system operators (DSO) will have to adapt to the new situation through the use of new technologies and developing operational procedures to handle faults[8] and routine maintenance outages (Nykamp, 2013). At low penetration, distributed generation can have the same effect as that of a reduction in load (Pudjianto, *et al.*, 2013). However at high penetration of distributed VRE generation, distribution systems can change from passive to active, *i.e.* they may produce more power than is locally consumed. In such cases, new roles for the distribution system may have to be explored in which it becomes a provider of additional system services such as power dispatching and local load control. This would

7 Through the cooperation, TSOs share information on the need for control power in their zones. The TSOs with an oversupply of electricity will deliver power to the zone of the TSO with an undersupply of electricity. As a consequence, the demand for control power of each TSO is reduced.

8 A fault is an event occurring on an electric system such as a short circuit, a broken wire, or an intermittent connection (NERC, 2015).

have to be done in coordination with transmission system operators (Hammons, 2008).

Furthermore, present systems are not designed to handle reverse flows, which cause difficulty in operating the distribution network, especially during faults and planned outages. As part of these new system operations, safety of personnel and equipment has to be ensured in case of unintentional islanding due to faults in systems with distributed generation. They can also require replacement of metering equipment, which are designed for unidirectional power flows (Dondi, *et al.*, 2003).With increased incentives for deployment of distributed generation such as net-metering and feed-in tariffs, but not enough incentive to invest in measures to upgrade the distribution grid, new regulatory practices may be needed to facilitate required investment to allow them to be integrated in the grid.

VRE generators will need to fulfil additional requirements and provide services traditionally provided by conventional plants as the share of VRE increases. These requirements may include voltage control through the provision of reactive power and fault ride-through capabilities. This will require the latest power electronics (which are slightly more expensive) to prevent adverse effects of voltage waveform distortion (MIT, 2011). Additional services like frequency-response and operational reserves provided by both VRE and dispatchable generators would acquire an increased importance at higher VRE shares (NREL, 2012a).

Technology companies and manufacturers would have to work towards developing technology standards and establishing communication protocols for smart grid technology in cooperation with industry and government stakeholders to ensure interoperability of equipment. Issues such as data processing capabilities, data sharing agreements, privacy laws, communication protocols and data security measures need to be considered and introduced.

Energy planners and regulators may need to change their power system planning from one that considers demand projections to one that also considers the location, type of generation and capacity factor. Flexibility will become increasingly important as a guiding principle (C21, 2015). Energy planners may require rethinking of traditional transmission system topologies to be able to transmit power most efficiently and consider additional technical specification for connections (EWEA, 2015). At the same time, the geographic spread of different renewable energy technologies can be used to find complementary synergies in the type and location of resources to reduce the effect of sudden changes in power resources. For remote areas, coordination between new installations and corresponding grid infrastructure will be required (Zhang and Li, 2012) and newly established renewable energy generation zones can be considered (Hasan, *et al.*, 2013). Increased cooperation between different regional planning authorities and system operators would be required to make the most of such interregional variations (IRENA, 2015h). This needs to be accompanied by long-term grid planning to undertake appropriate reinforcements to avoid grid congestion.

In general, the role of regulators will become more complex as the number of generators in the system increases. For example, regulators are generally responsible for consulting the generators and installers on the requirements, and to ensure that the system operators draft, implement, enforce and revise the grid codes across all participants. Smart grids, storage, and micro-grids are increasing the possibility for non-traditional stakeholders to enter the power system and provide grid services, which would make the role of regulators more complex. On the other hand, some of the functions of regulators might be embedded within the technical specifications of the power electronics as these technologies evolve.

The regulators will also need to revisit their procedures to schedule generation, which in some countries is governed by market designs. The main challenge will occur in systems that have limited demand growth, and where the addition of VRE will create a structural surplus of power generation capacity (IEA, 2014b). If these systems are governed by markets competing on marginal costs, VRE generators will always win over conventional power plants, because renewable power generation has virtually no generation costs (IRENA, 2015d). This would lower spot prices when VRE power generation is available, but could increase spot prices when VRE generation is not available (Tarroja, *et al.*, 2012). At the same time, more flexible power plants like gas-fired power stations will become more important to ensure load following in cases where supply does not match demand.

The actual impacts of VRE power generation on the markets is highly dependent on the specific conditions (including previous and existing support policies for VRE), the costs of VRE compared to alternative generation technologies, and the share of VRE. For example, in Germany the spread between peak and off-peak spot prices has been reduced, because solar PV systems are producing electricity when demand is high. In the last couple of years, this has reduced the arbitrage potential for energy storage facilities such as pumped-storage hydro plants (Hildmann, Ulbig, and Andersson, 2011). However, if the share of solar PV continues to increase the opportunities for arbitrage are likely to rise again.

The general public and non-governmental organisations will also remain important stakeholders to consider in the power sector transformation. Whereas there is some experience in engaging the public in the development of utility-scale wind parks, the integration of VRE will also require new infrastructure projects. In these cases, the public will need to be informed and involved as early as possible in the development of new transmission network, and strong regulations and satisfactory compensation mechanisms need to be in place to minimise the impacts on local communities and the environment (Boie, *et al.*, 2014).

2.2 New stakeholders

Due to the modularity of VRE technologies, the power system will attract a large number of new generators. For example, German utilities owned 3% of the installed solar PV capacity and 10% of the installed wind power capacity in 2013, while individuals, farmers, and communities owned around 50% of solar PV and wind installed capacity (AEE, 2013). Other stakeholders with substantial shares are project firms, investment funds and banks, and industrial users producing their own electricity.

Some of these new VRE generators may develop utility-scale plants, but the majority of owners will install distributed generation. This means that the number of entities playing an active role in the power sector will increase dramatically. For example, solar leasing companies essentially own a large network of distributed generation, which at an aggregate level could be used to play a more active role in energy markets.

The consumer will also take on a completely new role, and will be able to play an active part in providing electricity to others (IEA-RETD, 2014). On the one hand, individual households, farmers, and industrial users can produce their own electricity (the so-called prosumers) and feed this electricity back into the grid or to other users. In this respect, new companies are entering the power sector aggregating distributed generation technologies located at consumer-sites to pro-actively engage in the market (the so-called 'supply aggregators'). On the other hand, distributed generation combined with smart grid technologies allow consumers to play a more pro-active role in demand side management. This role is also taken up by new companies that aggregate demand side services across a number of customers (the 'demand aggregators'). A better understanding of consumer response to feed-in policies, advanced pricing and demand-side management measures will need to be developed to determine the extent of the role they can play in balancing power flows. For example, system operators could adopt a range of new demand response programmes to support the integration of VRE (Navigant Consulting, 2012).

Distributed VRE will also attract a new set of financing institutions and investors to the power sector. Traditionally, large investors and pensions funds view utilities as stable investments as they operated in regulated market with limited competition. VRE is one of the main drivers that has changed this situation (Gray, *et al.*, 2015). Green bonds issued by development banks, corporate investors and municipalities as well as 'yieldcos' (publically traded companies formed to own power plants and pass most cash flow to investors as dividend) are new players that are entering the market (Frankfurt School-UNEP Centre, BNEF, 2015)

The emergence of smart grid technologies may create a new information paradigm, which can enable the intelligent management of supply, demand and storage to plan and operate the various elements of the power system efficiently. Their increased deployment can lead to functions such as information collection, processing and control, playing a big role in the future. These can help power system operators better manage dispatch in real time; allow system operators to better observe and control power systems; enable retailers to implement real-time costing for electricity, among other applications. It is important to note that development of capabilities and defining a regulatory framework needs

Table 3: New stakeholders in the power sector transformation

New stakeholders	Relevant activities
Non-utility generators	Generation by individuals, farmers, communities, project firms, banks, industrial users;
Prosumers	Self-consumption; Net-metering; Grid feed-in
Aggregators	Grid support services (through supply and demand) through energy service companies, solar leasing firms
New financers	New investment streams from development banks; municipalities, yieldcos, crowdfunding; New ownership and finance models
Technology providers	Development and implementation of smart grid technologies, storage technologies, microgrids
ICT companies	Data collection, sharing, analysis and security
Consumer service companies	Building energy management systems
Car manufacturers	Electric vehicles for VRE integration
Emergency services	Anti-islanding; Reverse power flow concerns

to accompany the emergence of this new functionality to realise its full potential.

Within this paradigm, there are two new stakeholders groups that are emerging: consumer service companies and car manufacturers. First, building energy management systems are increasing opportunities to manage electricity demand locally and thus provide services to the grid. Furthermore, they can be used to support the integration of distributed VRE. Second, electric vehicles can be used to support the integration of higher shares of renewable energy. At a local level, electric vehicles could be coupled to building energy management systems to discharge power back to connected buildings and homes. At a larger scale, electric vehicles can be used to provide a host of system services to the grid (Hahn, *et al.*, 2013). The batteries from electric vehicles can potentially also be used to support VRE deployment in off-grid systems (Ambrose, *et al.*, 2014).

3. DATA COLLECTION AND ENERGY PLANNING

A national roadmap should be supported by processes to collect, share and use data on renewable energy resources, power generation, flows and demand profiles to develop and evaluate grid integration policies, as well as an institutional process for long-term planning of generation capacity and networks. This chapter discusses what information is required, and how it is relevant for the selection of different grid integration strategies.

The power sector is an industry that changes relatively slowly. Large centralised power plants are built with lifetimes of 30 or 40 years in mind, which means that the generation capacity built in 2015 will in many cases be around beyond 2040. Similarly, the transmission and distribution networks are built to last for 40 years or more.

Consequently, a national roadmap for the integration of renewable energy should not only collect data on the past and current experience, but also attempt to assess what the power system will look like beyond 2040. Figure 4 provides an overview of the key processes that need to be in place to ensure that sufficient data is available for the development of a national roadmap.

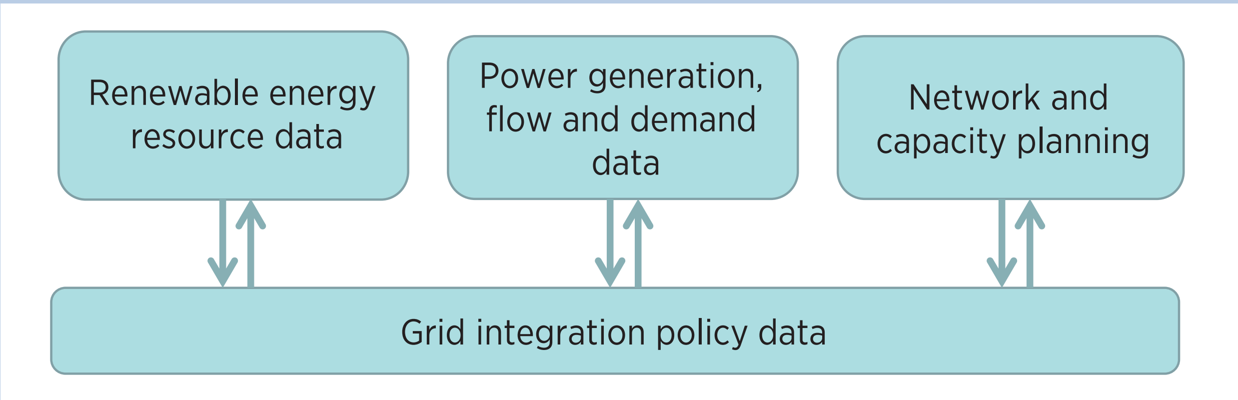
Four categories of data needs can be distinguished: 1) data on the renewable energy resources and their location within the country, 2) data on the existing and future generation mix, and network topography, 3) data on power generation from the individual plants, power flows across the network, and data on current and future demand for electricity, and 4) data on the impacts of VRE on the management and operation of the grid.

Finally, it is important to ensure that the impact and effectiveness of any existing grid integration policy is measured, and fed back into the revision of existing or development of new grid integration measures.

3.1 Renewable energy resource data

Mapping and the detailed assessment of renewable energy resources is required to inform decisions about resource allocation and planning at a national level. Knowledge about the limit of the resource, its geographic distribution and accessibility is needed to formulate actions to create an ecosystem in which the resource can be utilised. Assessments on a large scale can be useful for utilities, independent power producers and planning authorities for integrated resource planning. Reducing uncertainty about the resource can help in planning of generation and grid expansion, taking

Figure 4: Data needs for a national roadmap on renewable energy grid integration



environmental, financial feasibility and socio-economic factors into account. Often, due to large geographic distance between high yield sites and existing grid infrastructure, a trade-off between high productivity and grid accessibility might be involved in making such decisions, which can be better assessed by decision makers with such studies already in place. In this respect, IRENA's Global Atlas[9] provides access to more than 1000 datasets with renewable energy resources, visualises this data in renewable energy resource maps, and can overlay the maps with additional information on roads or grid infrastructure.

Assessment at a smaller scale and over longer time period is very beneficial for planning and investment in new projects. In many cases, such data is closely guarded proprietary information. Detailed site assessments required for new projects increase costs for new entrants, putting large manufacturers and project developers at an advantage. Publically available data can reduce this information asymmetry and can lower costs, attract investment, remove barriers to entry and promote competition.

Since resource assessment requires continuous data measurement over a span of several years in order to account for inter-annual variations, this is an activity which needs attention at the earliest to enable renewable energy and network planning. Rich renewable energy resource data (historical or modelled) alongside with load data (section 3.2) are also critical for grid integration studies.

3.2 Technical and economic data on generation, power flows, and demand

Technical and economic data on power generation, grid characteristics and electricity demand can be useful for several actors in the power sector, including system operators, planners, decision makers and researchers. System operators have historically developed expertise in managing power flows from vast experience with system operation and data collection. However, with increased variability and uncertainty on the supply side, measures need to be taken to enable them to adapt to the new system operation paradigm. For this purpose, maintaining and making available detailed datasets of both conventional and VRE generation can be very helpful. However, these are very rarely available at a level of sufficient detail or even at all.

The rapid progress and cost reductions in VRE and smart grid technologies, a concerted effort is needed to ensure publically available up-to-date region-specific data on their cost and performance systems (IRENA, 2015d). One additional data collection requirement for VRE are weather forecasts, which need to be converted into generation forecasts. Continuous measurement of power generation and re-evaluation of forecasts based on actual generation (so-called forecast error data) can with time help develop expertise in using weather forecasts to estimate power generation for grid operation.

Historic power generation datasets, if available, can also be valuable for power system studies for planning and evaluation of generation and grid infrastructure. For example, Denmark supports its long-term grid planning through the use of historical datasets for consumption and wind generation to determine generation needed from conventional power plants. More recently, Colombia has revised its regulation on the basis of historical generation data from wind turbines (see Box 13). In the absence of such datasets, power generation data has to be simulated from historic weather records, which may not be ideal for such applications.

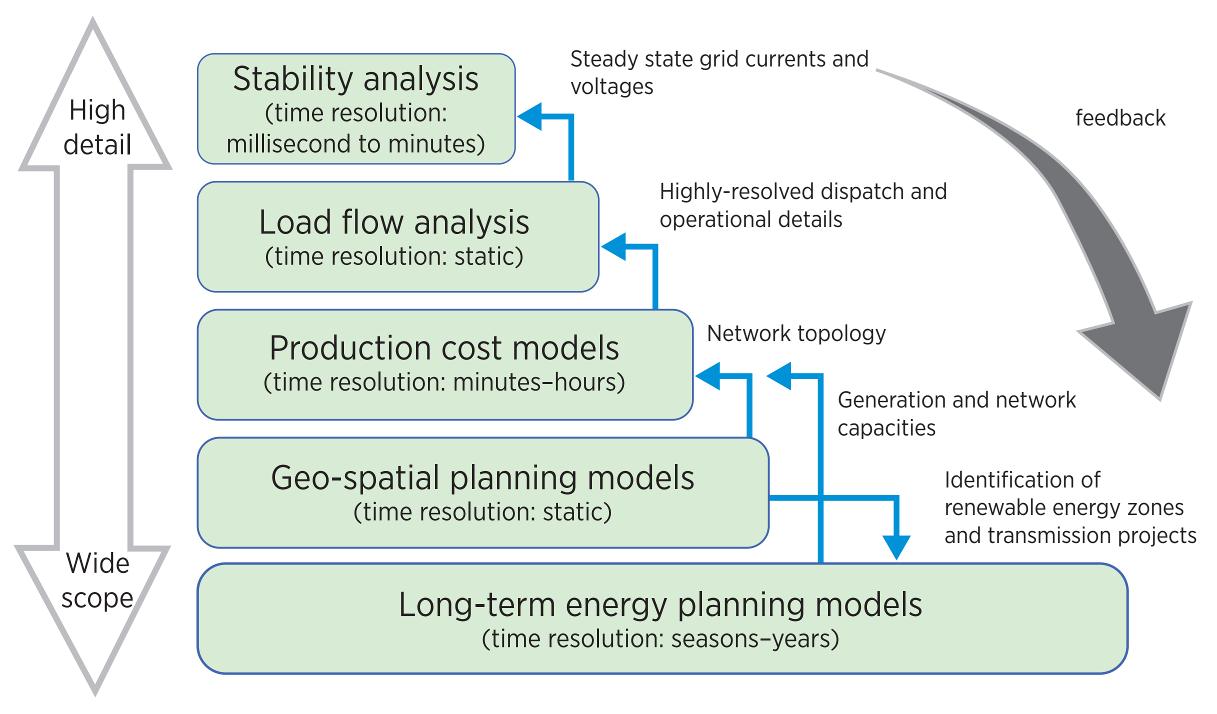
In addition, data is also useful for the evaluation of specific grid integration projects. Analysis based on real power generation data can reduce risks associated with grid integration measures, and can help promote and inform decisions regarding private investment in VRE, conventional generation, and grid infrastructure. The compilation of datasets on costs, performance and technical specifications of existing projects is therefore an iterative process, whereby the introduction of smart grid technologies to support VRE integration can simultaneously be used for the evaluation of new projects for investors and policy evaluation.

3.3 Network and capacity planning and modelling

Planning and construction of grid infrastructure and generation capacity usually takes place over very long time scales. This can often be much longer than the

9 *http://irena.org/globalatlas*

Figure 5: Different tools and analyses for energy system planning and design and their interaction



Source: IRENA, 2015c

time required for implementation of wind or solar power plant projects. This, along with the long lifetime of grid infrastructure components, necessitates long-term planning in anticipation of future capacity addition, demand and reliability requirements.

Power system modelling is a key tool to evaluate the different available technological options for long-term network and capacity planning. For long-term planning, a deterministic scenario-based approach have been used to model different possible scenarios of evolution of the overall capacity mix and to optimise grid development plans. Many of the existing models have been used to evaluate scenarios with high shares of variable renewables. For load flow analysis, other models are available that have been deployed to assess the most cost-effective way to use the existing generation mix and to identify potential reliability and security issues in case of any faults (Connolly, *et al.*, 2010). Figure 5 provides an overview of the different modelling tools available to support the planning, management and operation of power grids.

With the growth of VRE, the approaches and the associated power system models for planning may have to be re-evaluated (Weber, *et al.*, 2013; IRENA, 2015c). Increased uncertainty regarding the capacity and location of new generators (in addition to uncertainties related to technology costs, regulations, market conditions, etc.) can make long-term modelling impractical to implement when founded on a scenario-based approach, due to the wider range of possibilities. Planning bodies may have to consider a shift to modelling techniques that are based on risk assessment and probabilistic techniques, many of which are currently under development and discussion. Simultaneously, the rise of VRE means that these models have to be enhanced to weigh the costs of grid integration measures against the benefits of effects such as increased reliability, reduced curtailment, higher plant load factors, deferred grid infrastructure investment and lower requirement for reserve capacity (Poncelet, *et al.*, 2014; EC, 2015).

Assessment of energy storage potential or alternative end-uses of electricity will also become more important as VRE shares increase, especially for isolated systems. Thermal energy storage options are generally the most cost-effective solutions, and can be used to convert electricity into heat. For example, electric boilers are

Box 2: Grid investment needs for VRE expansion

Grid investments for renewable power generation

Grid investments for integrating hydropower, geothermal power generation, or biomass power generation are not very different from conventional power generation, except that hydro and geothermal resources are location-specific and may require additional transmission lines to transport power to demand centres. For example, China has built a number (ultra-) high voltage direct current (UHVDC/HVDC) lines over 1,000-2,000 kilometres to connect hydropower plants in the Southwest with demand centres in the East.

Integrating large volumes of VRE may create additional investments to reinforce and/or expand the transmission network to access renewable energy source or to have sufficient capacity to avoid overload. In distribution networks, investments may be required to resolve potential problems with voltage stability, phase imbalance or control and protection technologies for back feeds due to the variability and local power generation.

IRENA has developed a methodology to analyse additional investment needs for the expansion of VRE. This methodology has been tested and applied in five countries, and the results suggest that grid investments may vary substantially at a national level, but usually remain small compared to the investment in generation capacity. For example, Germany has added 5,000 kilometres of new high voltage lines (approximately costs of EUR 5 billion) since 2006, whereas total investment in renewable energy generation capacity amounted to almost EUR 9 billion in 2013 alone.

An important lesson from the analysis is that grid investments should not be seen in isolation, but should focus on the optimisation of total system costs, considering the costs of renewable energy and conventional generation, transmission and distribution networks. In many cases, it may be efficient to accept higher grid investments to reduce the overall generation costs in the power sector (IRENA, 2015j).

already being used to convert excess electricity into warm water, and stored in boilers until it is used by the consumer. Bulk electricity storage technologies like pumped-storage hydro power plants already play an important role in balancing power systems, and their role will grow as the share of VRE increases. An early assessment and analysis of the role of pumped-storage hydro is important, because its initial cost (and hence extent of deployment) depends heavily on availability of geographically suitable sites. Distributed electricity storage technologies may be particularly cost effective in combination with VRE generation in remote or island locations where expensive diesel generators can be made to run more efficiently (IRENA, 2012; IRENA, 2015e). The integration of the power sector in end-use applications will also become more important, such as the electrification of transport, the use of heat pumps in the building sector, or assessing productive uses of electricity in desalination or industrial processes.

Micro-grids present a new alternative to the traditional grid-connected power delivery model, particularly in rural areas or remote areas with diffuse population, where the costs of transmission and distribution become much higher. Localised studies to identify the generation, control and distribution technologies based on local conditions and resources need to be undertaken to benefit from their application.

Interregional modelling will also become important with a need to collect and process data and realise the benefits of a power system with a wide geographic reach, and hence, the ability to draw on a geographically diverse set of VRE generators and balancing resources, as such barriers to planning need to be addressed. Such networks may require coordination across different regions, each with separate actors responsible for planning, approval and operation. Integrated power system planning with increased coordination between stakeholders operating at the local, national and international level for projects spanning administrative boundaries can prove to be a challenge for the realisation of such projects.

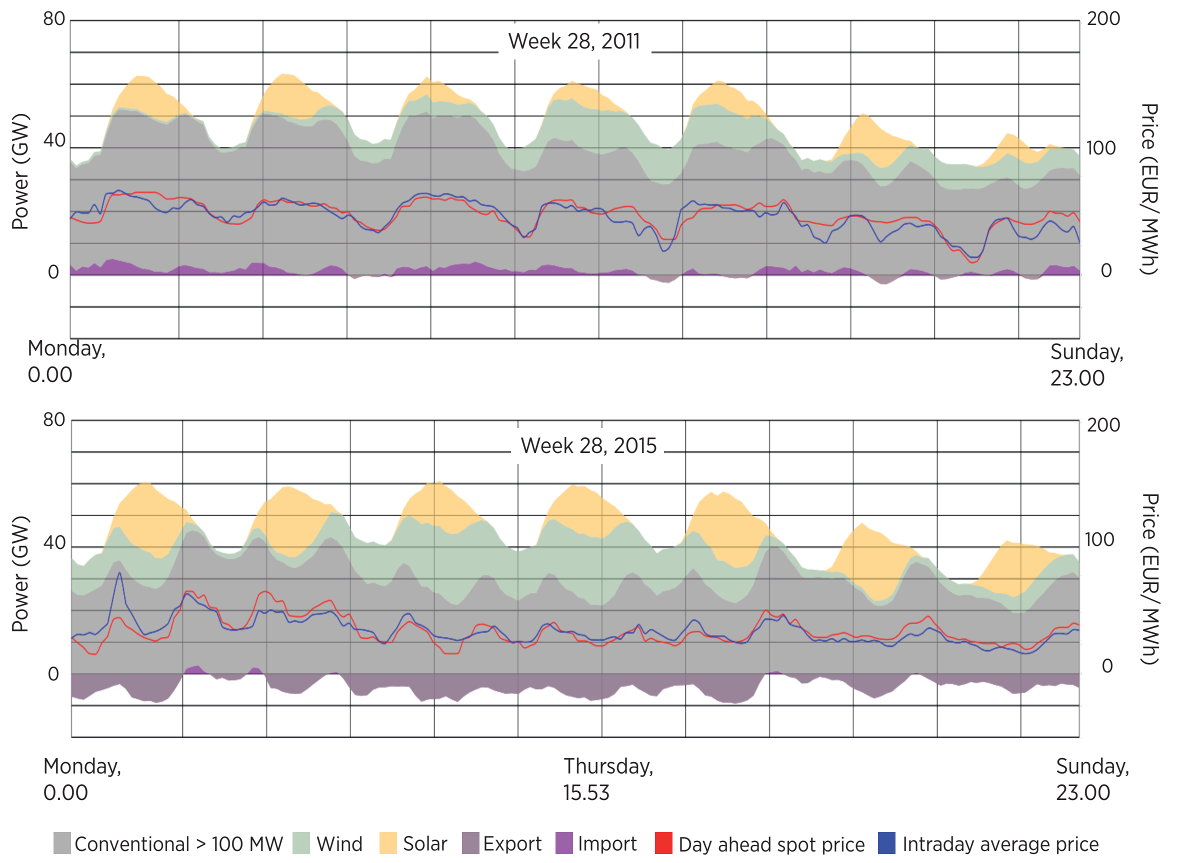
3.4 Grid integration policy data

Data collection should be an iterative process that ultimately results in more effective and more efficient grid integration policies. This means that data should be collected before and after the development of a national roadmap on VRE grid integration.

A good example of data collection to support the impact of grid integration policies is provided by the Fraunhofer Institute for Solar Energy Systems (Fraunhofer ISE, 2015). Based on these data sources, Figure 6 shows a comparison of power generation capacity and spot prices during a summer's week in Germany in 2011 and 2015. The data shows that day ahead spot prices and intraday spot prices in 2011 where highest during between 10.00 and 17.00 during work days, whilst in 2015 the spot prices were more volatile during the day with higher prices during the mornings and evenings.

The information on past and existing policies aiming to facilitate grid integration, their performance, and details about the context in which they were applied can be useful for inter-country learning. They can also be a valuable source for stakeholders to know the policies and regulations in place, enabling them to make better informed investment decisions. At a global level, existing databases with information about renewable energy policies need to augmented with information on policies intended to increase the flexibility of the system.

Figure 6: Comparison of electricity production and spot prices in Germany between 2011 and 2015



Source: Fraunhofer ISE, 2015

4. ASSESSING CONDITIONS OF FLEXIBILITY

The selection of grid integration measures not only depends on the share of variable renewable energy, but also on the geographical conditions, development status, and foreseen renewable energy targets. Furthermore, the grid integration measures should match the existing flexibility options within the current power sector. This chapter discusses the different country flexibility options affecting the relevance of grid integration measures.

Before evaluating different options for grid integration and recommending steps to practically implement them, it is important to have a clear vision of the existing context, future targets and their implications for a grid integration strategy. As a rough measure, three additional measures can be used to assess the challenges associated with the integration of VRE at a national level: 1) the level of interconnectedness, 2) the level of newly built power generation capacity needed, and 3) the rate of change in VRE shares

Isolated grids on islands and remote areas will face more severe challenges than countries with large balancing areas or countries that are highly connected with their neighbours (*i.e.* Denmark or Germany). Countries that are experiencing growth in electricity demand and are expanding their power generation capacity (*i.e.* Brazil, China, India, South Africa) will find it easier to create a generation mix and network topology that is favourable for the integration of VRE, than countries where VRE power generation capacity is replacing existing assets (*i.e.* Germany, US). Finally, countries that are incrementally increasing the share of VRE will find it easier to adapt than countries that are rapidly increasing the VRE share.

Within this context, previous studies have identified a number of power system properties that determine existing flexibility options within given power systems (see Table 4). The IEA identified seven characteristics, while IEA-RETD identified four characteristics. In this

Figure 7: Country characteristics that determine the ease of renewable energy grid integration.

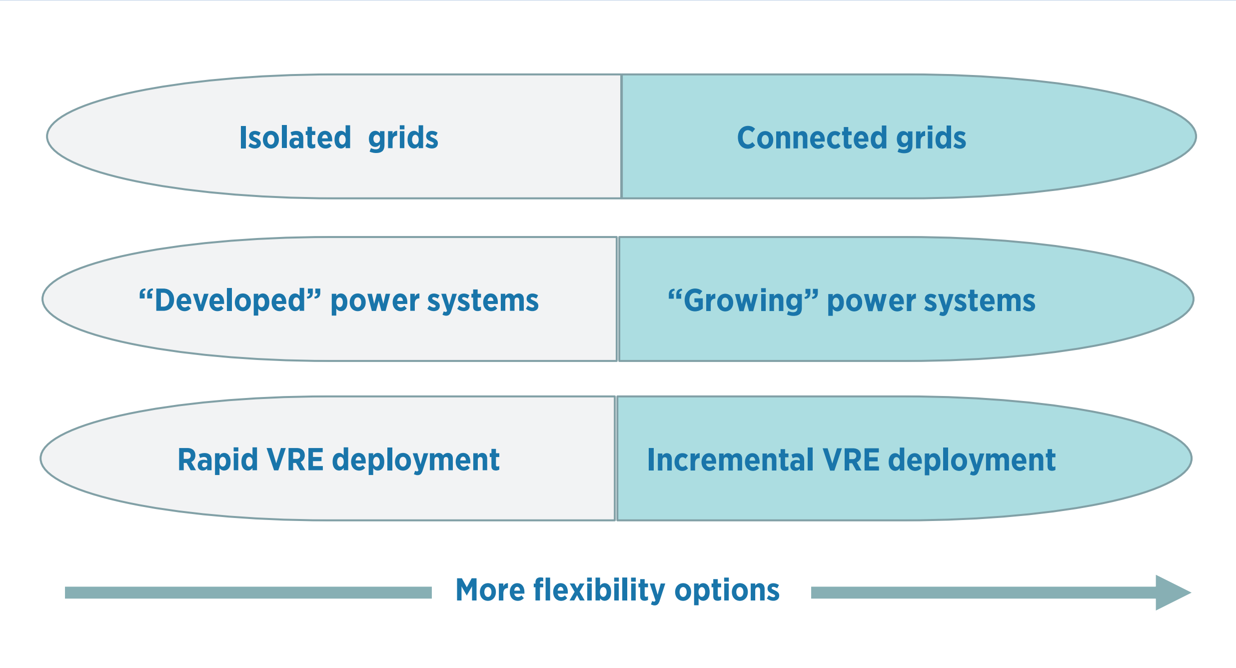


Table 4: Power system properties affecting VRE integration

Power system	Flexibility conditions support VRE integration
Power generation mix	Flexibility of dispatchable generation portfolio (including pumped-storage hydro)
	Geographical spread of VRE
	VRE portfolio
Grid infrastructure	Large balancing area
	Strong transmission and distribution networks
	Interconnection and access to neighbouring systems
	Advanced operational capabilities for grid management
Institutional framework	Dispatch models based on short-term intervals
	Investment opportunities
	Flexible demand

Source: Based on IEA, 2014b; IEA-RETD, 2015

chapter, we group these characteristics into three categories. Each category will require data, information, and engagement from different stakeholder groups.

4.1 Power generation mix

The power generators, grid infrastructure, and consumers form the main physical components of a power system. A thorough understanding of their characteristics can help determine opportunities and key focuses for measures to increase power system flexibility.

The current and future generation portfolio in a power system plays a key role in defining its grid integration strategy. The influence of VRE becomes noticeable beyond annual shares of 2%-3% (IEA, 2014b), but up to around 15% no special measures may be required to manage the variability introduced. Conventional methods used by system operators to deal with variations inherent in the power system – due to demand side variations, generation failures, line faults, etc. – can be sufficient at low VRE penetration. Technically, it is even possible to integrate annual VRE shares of 25% to 40% with existing levels of system flexibility (IEA, 2014b). The share of renewable generation, its technological maturity and cost competitiveness in the region dictates the role it can play in providing services, such as load following, frequency and voltage regulation, and fault ride-through. Beyond this, accommodating higher shares in the future would require advanced planning in anticipation of changes in the power system.

The technology, design and age of the stock of dispatchable power generation determines the flexibility of the system, while a mix of renewable energy sources significantly decreases the need for additional flexibility. Flexible technologies such as hydropower and open cycle gas turbine power plants have high ramping rates, short start-up and shut-down times, and can be used to balance variations on shorter time scales. On the other hand, power systems that largely depend on baseload power plants would have a lower potential to rely on supply-side flexibility to balance power flows economically. Newer power generation technologies are generally more flexible than older stock, which would require increased maintenance to support frequent cycling and may lead to reduced plant life due to thermal and mechanical fatigue. The physical components and operational procedures may have to be modified to adapt older stock to be able to operate them cost-effectively.

The presence and potential of power and heat plants capable of storing energy (such as combined heat and power (CHP) plants and pumped-storage hydro power plants) also needs to be considered. This can also play a significant role as a balancing strategy, as in the case of Denmark.

Power systems, which have historically evolved to use large, centralised generation plants may require special measures to build technological and operational capability to be able to deal with distributed VRE generation. On the other hand, system operators with past experience in dealing with conventional distributed generation can be at a relative advantage by leveraging their experience, while integrating distributed VRE into the system.

4.2 Grid infrastructure

The state of the transmission and distribution grid infrastructure with respect to geographical coverage, adequacy and reliability is an important determinant for VRE integration. A strong and well-connected power grid ensures that generators are guaranteed dispatch, that demand can be met and that the flexible resources in the system can be used in the most efficient way. Grid infrastructures need to be maintained and updated to keep up with increase in demand, increase in VRE generation at certain locations within the power system, or change in power flow pathways resulting from new generation plants. Fragmented or congested grids may prevent the least-cost set of resources from being available for use, resulting in higher costs being incurred to meet demand.

The options to improve the grid infrastructure may be limited depending on the country situation, and therefore need to be considered. As discussed in the introduction, isolated systems are more constrained than grid connected systems. Large connected systems can increase the geographical area over which power balancing can be made, by making available a wider range of balancing resources and reducing the geographic and (in many cases) technological concentration of VRE generation in the system. Isolated systems may have to rely on alternate strategies, such as energy storage or demand side management to balance power flows.

Similarly, countries with a developed grid infrastructure will need to focus on options to connect new VRE generation to an existing grid, develop operational

Box 3: Economic evaluation of smart grid technologies for VRE integration

The costs of most technologies to support the integration of higher levels of VRE are reasonably well understood, although the costs may differ per region and may change rapidly over time. For example, the costs of high-voltage direct current converter stations differs by a factor three between China (USD 100/kW) and German (USD 275/kW) (GlobalData, 2015b) and in Germany the costs of battery storage systems dropped by 25% during 2014 (IRENA, 2015f).

IRENA has developed a cost-benefit analysis to assess the impacts of smart grid technologies, especially for developing countries (IRENA, 2015k). The benefits, however, are less easy to define and quantify. Some of the benefits, such as decreased operations and maintenance (O&M) costs, are relatively clear. Others such as improving consumer choice or enhancing grid resiliency clearly have value, but putting a dollar amount on these types of benefits is quite challenging.

An additional challenge in evaluating grid integration technologies is that the benefits often flow to multiple stakeholders. Consumer choice is of value to the users, but probably of less direct value to a system operator. Similarly, high VRE shares may reduce the overall system costs for producing electricity, but may raise the expenditure on O&M for the system operator.

Finally, there are multiple interactions between technologies. In many cases, expanding the transmission and distribution network is seen as the cheapest option for VRE grid integration. However, investments in smart grid technologies to increase the reliability of the system may simultaneously reduce transmission and distribution investment needs by optimising use of existing infrastructure.

practices and adapt the grid to better manage variable and distributed power generation. A developing grid infrastructure provides a green field where VRE expansion can be integrated into a grid expansion plan, used to promote grid access, or strategically located to increase reliability and remove transmission bottlenecks. Countries with developing power systems looking to adapt renewables as a strategy to achieve energy security can consider alternate pathways instead of the traditional centralised generation-based power system. Their potential to learn from countries currently in the process of adapting to a distributed generation-based model and to leapfrog the intervening stage needs to be explored.

The capabilities to operate, control and manage the grid infrastructure is also an important factor for flexibility. In particular, the experience with using smart grid technologies, modern control centres, data processing, and communication protocols with generators is an important asset that will assist in VRE integration. There may be enabling infrastructures that may aid the integration of VRE. For example, countries with well-developed communication networks and expertise in ICTs may be better placed to establish a smart grid infrastructure.

4.3 Institutional frameworks

Factors such as the regulatory structure, and the wholesale and retail market structure play a key role in power balancing, grid investment and VRE development.

In a situation with a monopoly in power generation and supply, power balancing becomes the sole responsibility of the utility, which may prove to be a challenge. On the other hand, competitive power markets can be used as a tool for balancing power in the system. In general, it is important that price signals are being used to generation and demand is matched. In addition, price signals need to be complemented with mechanisms to raise investments for adequate grid infrastructure and accurate generation forecasting to enable them to be fully effective. Finally, markets or mechanisms that create price signals at shorter time intervals improve balancing options. Separate short-term markets for ancillary services can help fully utilise the responsiveness of the generation portfolio.

In cases where there is vertical integration between generation and transmission and distribution, there is a possibility of barriers for new generators' connections. This may create difficulties in attracting private investment in VRE generators, especially distributed generation and in remote areas. Unbundling can help remove any incentives to discriminate between generators for grid connection and access. Furthermore, a large number of utilities operating in small areas may create barriers for integrated wide-scale planning and execution of transmission expansion projects, spanning more than one such area.

The option for demand response programmes to provide balancing services is also an important framework to support the integration of VRE. The impact of demand side programmes depends on the characteristics of the demand response technique employed (for example, direct load control, advanced pricing, dynamic demand etc.), but also depends on various local factors. One of these is the size, location and nature of electric loads. Certain loads such as electric vehicles, heating, air conditioning and pumping are better suited for quick demand response, and others such as household lighting and many industrial loads may not be available for immediate response. Methods to assess the flexibility of demand need to be developed further.

Institutional frameworks governing energy efficiency measures should also be considered. Building codes or energy performance standards for industrial processes can free up existing grid capacity at both the transmission and distribution level, redubbing the need for investments in grids to integrated VRE.

Institutional framework for education and research also need to be considered. An adequate stream of funding is required to support development, deployment of adapted new technologies, procedures and human capacity, and the role of technology suppliers. Additionally public research and development (R&D) institutions in such a scenario need to be better understood.

5. ENABLING TECHNOLOGY OPTIONS

Technology solutions to support the integration of variable renewable energy are available, but efforts are required to understand their implications within the national context. This is particularly true for technologies that are still rapidly developing. This chapter discusses three strategies that can be adopted within a national roadmap to ensure that technological capabilities are in place to support grid integration measures.

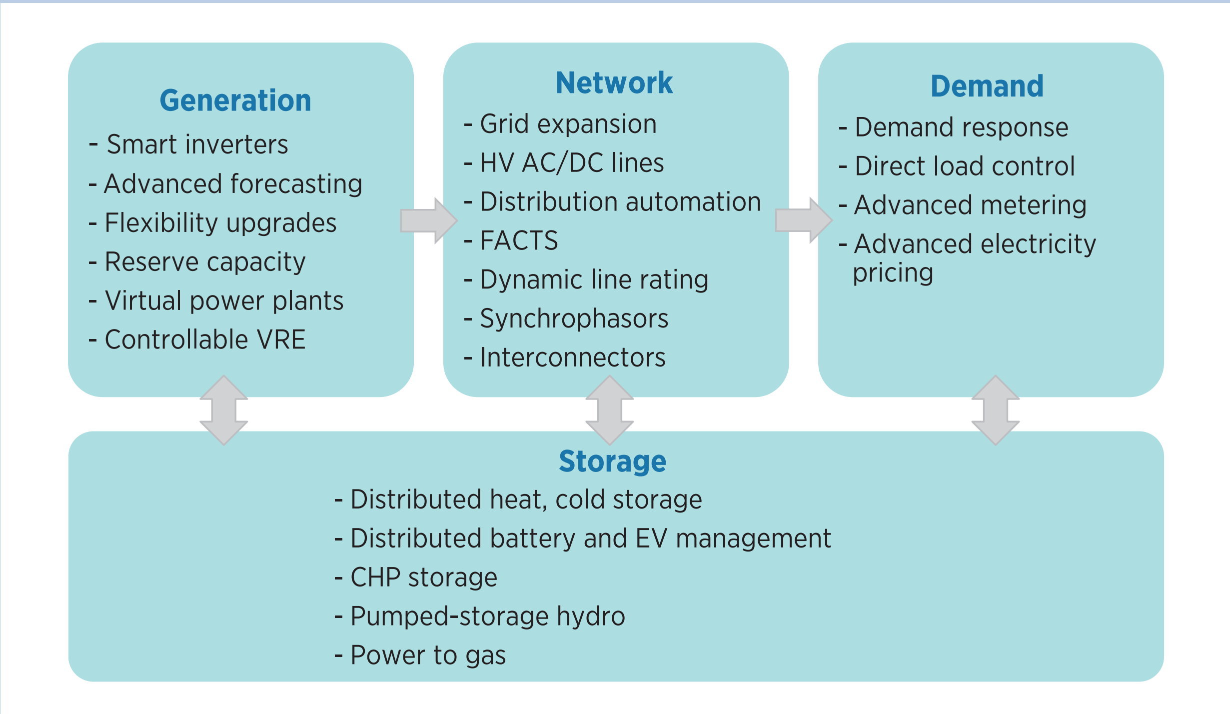
There are a large number of technical options available to support the integration of variable renewable energy into the grid. In most cases, these technologies can also and simultaneously used to improve the efficiency, effectiveness and reliability of the power system as a whole. Figure 8 categorises the different options according to the location where they would be implemented.

Detailed description of these different technical options can be found in a number of IRENA reports (IRENA, 2012; IRENA, 2013; IRENA/IEA-ETSAP, 2013; IRENA, 2015f) as well as the publications by the IEA (IEA, 2014b), World Bank (World Bank, 2013) and other national and international institutions.

The function, performance and value of these technologies is highly dependent on the specific power sector in which the technology is deployed, and the capabilities of the users. Furthermore, the technologies and capabilities of the users evolve over time affecting their function. Countries need to improve their capabilities in order to develop new technologies, adapt grid integration measures to their own context and to implement and operate them effectively. This chapter proposes a number of actions, which can be taken to support the development and implementation of technological options required to integrate a high share of variable renewables into a power system.

On one hand, there are countries such as China, Denmark, Germany, Japan, South Korea and the US that have decided to take the lead in research and development in grid integration and smart grid technologies

Figure 8: Overview of technical solutions for VRE grid integration



(see chapter 6). This has been achieved through a combination of applied research and learning from deployment driven by favourable policies. In addition to the immediate benefits in terms of increased capability to integrate VRE, such expertise can have long-term benefits. By assuming **technological leadership**, they can get a first-mover advantage in the second wave of technological developments required to shift towards a renewables-based system.

On the other hand, countries can choose to focus on knowledge spill-over from these initial efforts and build upon them. However, they need to place themselves in a position to do so, by ensuring they have the capabilities and institutions required to have sufficient **absorptive capacity**. Because of the highly specific nature of individual power systems, they can also benefit from both fundamental and applied research (in materials, meteorology, power systems, power electronics etc.) to develop the expertise to plan and upgrade their own power system. But perhaps even more significantly for developing countries, work is required to ensure that the institutional structure can facilitate the absorption and adaption of technologies from other countries. Either way, technology development requires experiences on the ground, and the creation of **demonstration projects**. In particular, the development of strategic niche markets provides an opportunity to examine the interaction between technology and the institutional frameworks in more detail. Different innovation strategies are available to support the development of technological leadership, absorptive capacity and demonstration projects (IRENA, 2014c).

5.1 Building technological leadership

R&D opportunities are available for all levels in the power system.

Generation: Research priorities in the long- and short term have to be established. For an immediate impact, a better understanding of the effect of flexible operation on conventional generation needs to be developed. This is especially true in the case of thermal power plants, where the equipment wear and cyclical operation can result in increased operating costs and reduced plant life. The exact impact depends on the technical specifications of the particular plant. The measures required in terms of technological specifications, retrofits, operational procedures etc. to minimise the impact on conventional generation need to be evaluated.

Research is required to increase the accuracy and reliability of forecasting systems to better manage existing VRE capacity. This is particularly important in power systems with geographically concentrated VRE generators. In such cases, even very small errors in wind speed or solar irradiance prediction can lead to very large deviations between the predicted and actual power production. The ability to predict power production accurately and well in advance can help balance power by scheduling production or through power markets. Smart inverters, when used to interface renewable energy generators in the grid, can mitigate problems such as voltage problems and frequency fluctuations. Their ability to contribute to centralised voltage optimisation needs to be explored by developing the necessary control algorithms.

Demand side: To date, demand side management has been used in certain cases as a way to reduce energy usage and to shave or reduce peak loads. While this has demonstrated benefits in terms of energy savings and reserve capacity requirements, work still needs to be done to develop customer response and direct control as a flexibility option. The sensitivity of consumers to price signals in terms of response time and consumption flexibility is not yet completely understood, making it less suitable for balancing power actively. However, its potential to add flexibility in combination with automatic response or direct load control needs to be explored. Research is required to automate these methods, deal with privacy aspects associated data collection, and to devise cost structures to implement them in cooperation with consumers.

The use of electric vehicles to support the integration of VRE is also an important area where more technological leadership is required. This includes technological development in the areas of super-fast charging, but also in the scheduling, planning, and use of charging stations, as well as software development for managing charging/discharging behaviour and control.

Network: The emergence of smart grids introduces the possibility of using disaggregated resources (including storage or electric vehicles) distributed through the power system in a coordinated way. It also provides the opportunity to better control resources in smaller independent segments of the power system in the form of microgrids. These may provide significant potential to add flexibility to the system, and efforts need to be made to develop control methodologies to use them in a coordinated way.

Developments in ultra-high voltage AC or DC lines and breakers are allowing for distant energy resources (including those located in the oceans) to be transported to demand centres, but they generally require larger, more expensive transformers, insulators and towers, and greater land area for clearance (MIT, 2011).

More work is required to bring smart grid technologies to maturity. This includes power electronics, as well as technologies, algorithms and protocols for data collection, communication and processing. Phasor measurement units (PMUs) can act as an improvement over existing transmission grid monitoring systems, based on supervisory control and data acquisition (SCADA) and remote terminal units (RTUs). However, new algorithms are being developed to integrate smart grid technologies into the system, to process the collected data for state estimation and to automate actions based on the collected data.

One problem associated with using smart grid technologies is potential for cyber-attacks in such a system. Security measures need to be built into the system from an early stage of development, considering the scale of damage that would be caused in case of an attack.

Storage: Energy storage technologies which could be viable in the coming years need to be identified to prioritise R&D, and mature technologies must be deployed. Thermal storage options in the form of district heating, electric boilers, and ice storage should be analysed in more detail, especially considering their potential role in VRE integration. More research on distributed electricity storage options – such as advanced lead-acid, molten salt, lithium-ion and flow batteries in the medium term and metal-air and solid electrolyte batteries in the long term – is needed to develop a diverse portfolio on storage technologies (IRENA, 2015f). Alternative storage options like power to gas need to be considered to provide balancing services over long periods of time.

Besides technological research, there is a need to identify the optimum type of technology and its precise specifications for particular applications. There are still no definite procedures for sizing and lifetime estimation of storage for supply side storage, storage in remote areas and islands, applications for frequency and voltage regulation etc. The definition of such procedures, along with information about cost-effective applications can help create viable business cases for storage technologies (IRENA, 2015e).

5.2 Developing absorptive capacity

A learning process is required when technologies for power generation, evacuation or storage developed and matured in one context are introduced to a new context. Without pre-existing technological expertise, training institutes and up-to-date knowledge, even mature planning techniques, operation procedures and technologies may not be effective. This can become a significant barrier for the introduction of new technologies. This problem can be particularly severe in countries depending on foreign aid or project implementation for renewable energy. Technology installation and training of personnel cannot ensure success beyond the scope or duration of the project. Particularly in small countries, attrition of trained personnel can have a big impact. It can negate such efforts in the absence of mechanisms to maintain organisational memory or to maintain a steady supply of trained personnel. Vocational training institutes and apprenticeship programmes urgently need to be set up in such cases to address the shortage of trained personnel.

Over the past years, there has been a trend of decreasing spending on research and development by electric utilities in developed countries, possibly resulting from increasingly liberalised and regulated power sectors in many of their economies. Whereas, state-owned utilities in emerging economies have increased their absolute R&D expenditure because of organisational growth. In this context, and with the requirement for exploring new technologies and strategies for the efficient integration of VRE, the role of public research institutions and equipment manufacturers becomes even more prominent.

The development of absorptive capacity cannot be separated from other economic policies, such as the availability of credit for companies, export schemes and stimulation of entrepreneurship, to name but a few.

5.3 Pilot and demonstration projects

The aim of pilot and demonstration projects is to understand how technologies can be and are used in real world applications, and to learn from mistakes. Test bed micro-grids and demonstration facilities, which accurately simulate real operating conditions, need to be developed to ensure the deployment and diffusion of grid integration technologies. Demonstration projects for storage technologies also need to be prioritised, with application at all grid levels, looking to improve cost and performance of existing technologies.

By demonstrating the operation and effectiveness of new technologies, others can take advantage of learning from early adopters, reducing uncertainty in performance and payoffs to encourage investment in these technologies. Several strategies are available to support the development of pilot and demonstration projects. These strategies include the development of a governance structure that interconnect all innovation related fields, coordination from national to local governments, the creation of niche markets through public-private partnerships, engagement of local communicates to ensure that social needs are reflected, and coordination across countries (IRENA, 2015g).

Furthermore, it is crucial to collect data and experience on the local application of VRE grid integration technologies. An IRENA analysis of 16 smart grid demonstration projects in Europe, Asia and North America showed that different technologies, regulations, and ICT practices can be combined in multiple ways to support the grid. In total, 23 different smart grid measures were introduced in the 16 projects and only 7 out of the 23 measures directly relate to the connection and integration of renewable power into the grid. The other 16 measures support the management of systems with high shares of renewables, but their primary function is to improve cost effectiveness, increase reliability, or support liveable communities. Box 4 provides an overview of the lessons learnt from this analysis.

Box 4: Lessons from smart grid demonstration projects for renewable energy integration

IRENA conducted an assessment of 16 smart grid demonstration projects in Asia, Europe, and North America. The following lessons for policy makers were derived:

- Engage with system operators from the start: The grid planning and operation will need to be adapted to the new types of generation and flexible consumers.
- Enable better collaboration between transmission and distribution system operators: They need to find a new collaboration mode: Distribution system operators will get roles similar to those of transmission operators. Questions of responsibility for balancing, voltage quality and overloads, stability will need to be solved.
- Engage consumers to provide balancing and metering solutions: Consumers and generators of electricity including storage will be key users who must strongly contribute to a well-functioning and robust electricity/energy system.
- Consider the total system cost including the grid, generation costs and all technology costs allowing for monitoring and flexible controls: The traditional natural monopoly regulation of the grids is challenged by flexibility needs of generation and consumption with lower marginal energy cost but higher and long-term investment costs.
- Find the right level of embedding ICT: ICT will create efficiency and total costs advantages and allows for different pricing models. The levels of automation will depends on trade-offs between system stability, security / privacy and investments into electricity/energy autonomy (microgrids).
- Support learning measures on linkages between different energy carriers. Complexity will clearly increase with the need to link to other energy carriers such as heat, gas, cold with the overall goal to decrease CO_2 emissions and to increase energy efficiency.
- Support learning measures on the integration of mobility: Electric vehicles an 'embedded' storage capacity, which is potentially available to support the grid. Integrating mobility storage in the right way into the other grid based energy system will contribute strongly to achieving higher shares of renewables, but also improve cost effectiveness, reliability and local networks.

6. VRE GRID INTEGRATION MEASURES

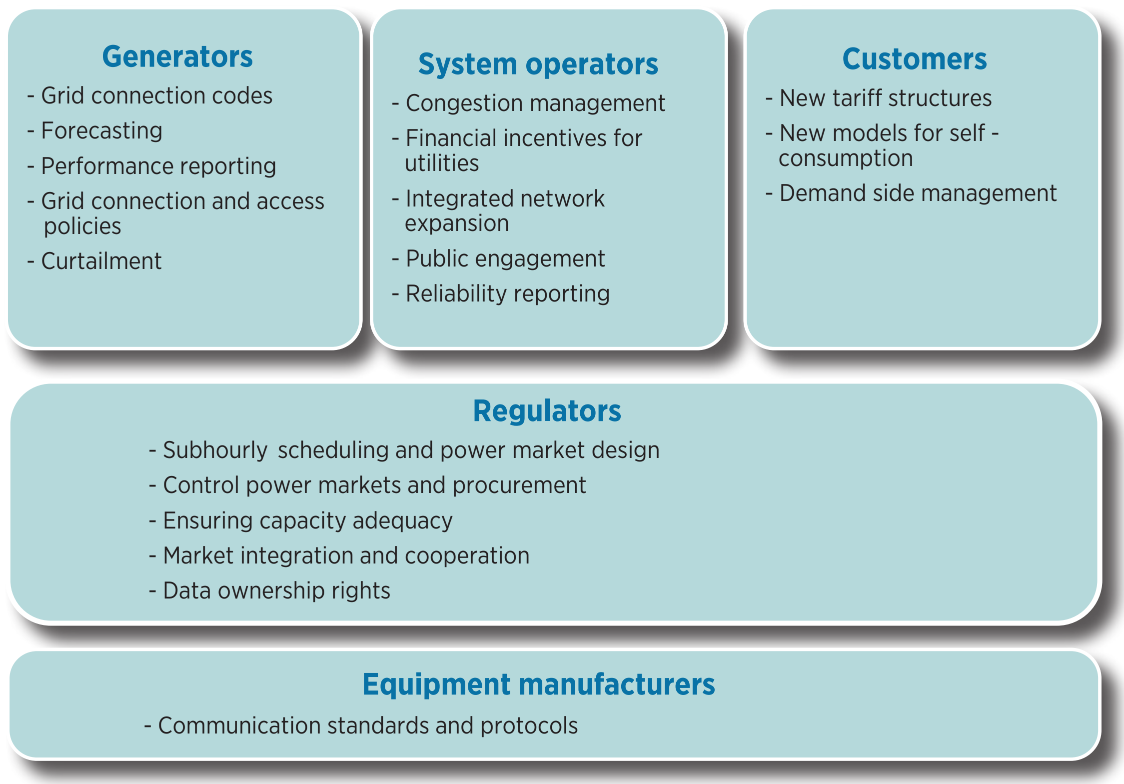
This chapter provides an overview of 20 grid integration measures that have been proposed to support the integration of variable renewables. The measures have been categorised according to the stakeholder group that would be most affected by the introduction of the measure. Furthermore, the data and energy planning requirements, flexibility conditions, and technology options available to support the implementation of these measures are listed. Each measure is accompanied by a case study.

Figure 9 provides an overview of the different VRE grid integration measures that have been proposed and discussed in a number of the existing reports on renewable energy grid integration (IEA, 2014b; Jones, 2014; IEA-RETD, 2015; World Bank, 2015; Ecofys, 2015).[10] The measures have been categorised according the stakeholder group that will be most affected (see Figure 9).

The VRE grid integration measures are described from the perspective of a national policy maker choosing those that are most relevant. As such, the summary tables provide information on:

- Who will need to be involved in implementation process (Step 1: stakeholder engagement)?
- What data and energy planning processes are needed (Step 2A: data collection)?
- What flexibility constraints does the measure address (Step 2B: flexibility assessment)?
- What technological capabilities are needed (Step 2C: technology evaluation)?

Figure 9: Overview of VRE grid integration measures discussed in international publications



10 The website 'Greening the grid' also provides an overview of different grid integration measures.

6.1 VRE grid integration measures for generators

There are four VRE grid integration measures that most directly affect VRE generators. Grid codes, grid connection and access policies are relevant for most situations and all levels of VRE shares, while forecasting, performance reporting and curtailment become more important as the share of VRE increases.

Grid connection codes

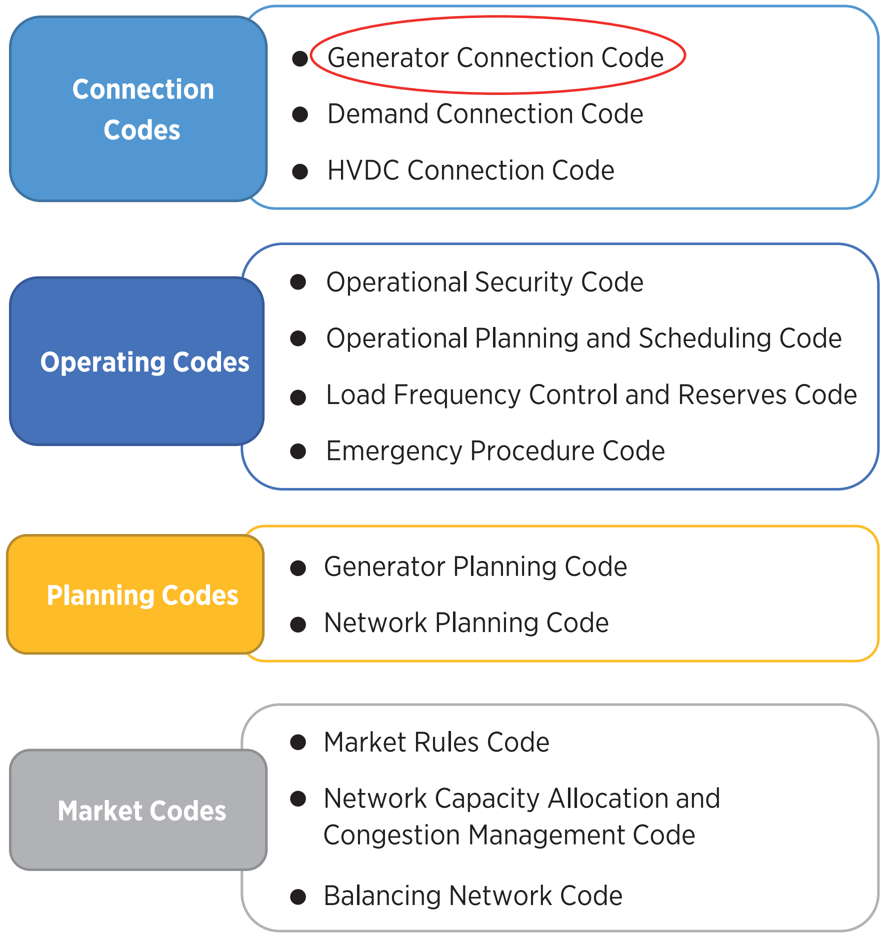
Grid codes provide rules for the energy market and power system operation. They include different sets of codes to enable network operators, generators, suppliers, and consumers to operate more effectively across the market. One group of codes are connection grid codes, which define rules for generators to connect to the power network while ensuring the security of the service to the end-user.

Grid connection codes prevent adverse effects on the power system characteristics and on the performance of other generators. Requirements include, *inter alia*, fault ride-through capabilities, active and reactive power control, ramp rates, power quality regulations and remote controlling capabilities. A platform for discussion and sharing experiences on grid connection

Table 5: Relevance of VRE grid integration measures affecting generators

Measure	Who should be engaged?	What data and planning is needed?	What flexibility constraints are addressed?	What technologies are required?
Grid connection codes	VRE generator; System operator; Regulator; Technology developer	Resource assessments; Generation profile and power flow data	Dominance by single VRE technology; Weak distribution networks; Limited operational capabilities	Smart inverters
Forecasting	VRE generator System operator; Meteorological agency; Regulator; Technology provider; ICT companies	Resource assessments; Generation profile data	Geographically concentrated VRE resource; Dominance by single VRE technology; Limited operational capabilities; Long dispatch intervals	Forecasting/ nowcasting tools; Control systems
Performance reporting	VRE generator; System operator; Regulator; Technology provider; ICT companies	Resource assessments; Generation profile and power flow data	Limited spread of VRE; Small balancing area; Limited operational capabilities	Smart inverters; Distribution automation; Communication protocols
Curtailment	VRE generator; System operators; Regulator; Financer	Resource assessments; Generation profile data	Dominance by single VRE technology; Limited spread of VRE; Small balancing area; Weak grids	
Grid connection and access policy	VRE generator; System operator; Regulator; Energy planner; Technology provider	Resource assessments	Concentrated/Dispersed VRE locations; Weak grids	

Figure 10: Example of different types of grid codes.



Source: Based on ENTSO-E, 2013

requirements, are the international standardisation processes such as the ones in the International Electrotechnical Commission (IEC) or the Institute of Electrical and Electronics Engineers (IEEE), amongst others. Country experts can benefit from engaging in this process to implement best practices in national regulations based on international standards.

The requirements can vary depending on the local conditions set out in chapter 4, such as size of the system, interconnection level, and generation mix. Even within a single large country, the technical requirements for connection can be adapted to the particular requirements for a region, depending on the VRE share and the power system characteristics. For example, Southern Australia has specific grid codes that differ from the rest of the country.

Overly cautious technical requirements may place unnecessary financial burden on project developers. This means that they have to be developed and revised as the national power system evolves (see Box 5). However, the precise timing of setting a particular code can be hard to assess. Countries can learn from the past experience of regions with high shares of VRE (and plan technical standards in advance for the future trajectory of VRE generation growth, reducing the need for measures such as caps for deployment or curtailments in generation (IRENA, in press) .

The link between national and regional grid codes will become more important with the regional integration of power markets. For example, ENTSO-E has developed a set of guidelines for countries in Europe to implement

Box 5: Grid codes – Denmark

Background: Denmark was a grid code pioneer, developing some of the first interconnection requirements in the late 1980s to deal with the increasing numbers of small wind and solar plants being installed in the distribution system. It has established well-defined grid codes to specify the properties that thermal and wind power plants must have to be connected to the grid to regulate capability and reactive power generation of the plants. Moreover, the transmission system operator Energinet established grid codes for wind farms to help support the grid to maintain voltage and frequency by providing ancillary services, such as active and reactive power control, frequency regulation and ride-through capabilities.

Results: Denmark is one of the few countries with strict grid codes imposed on wind generators, because it requires technical support from them for the operation and stability of the system due to the high penetration of wind in the generation mix. In terms of frequency regulation, when the frequency is between 49.5–50.5 Hz, the wind generators must remain connected and operate continuously at full capacity — for thermal units this range is between 49–50.5 Hz. When the frequency is between 50.5–52 Hz the wind generators must remain connected at least for 15 minutes and vary their operation between 60%–100% of active power depending on the TSO's instructions — in the case of thermal units, they must remain connected for at least 30 minutes and without any reduction in the power supplied. When the frequency is between 47–49.5 Hz the wind turbines must operate at 80%–100% of active power and remain connected a minimum time specified – ranging from 2 seconds to 5 hours depending on the frequency level. The further the frequency deviates from its nominal value (50 Hz), the less time required by wind turbines to be connected and the more flexibility in power output required from them; when the frequency is either above 52 Hz or below 47 Hz the wind turbines are allowed to disconnect from the grid. Moreover, Denmark also has one of the most demanding requirements for both ramp-up and ramp-down rates, where wind farms must be able to vary their active power ramp-rates (up and down) in the range 10%–100% of PN per minute upon request. In Denmark, grid codes have facilitated the integration of VRE in the grid, particularly to achieve higher penetration of wind power and subsequent displacement of large central power stations, while maintaining security of supply (one of the highest in EU) and certain quality standards. Similar grid codes are applied to wind turbines connected at the medium (60 kV) voltage level and below. Nowadays, wind turbines in Denmark accounts for almost 30% of the total electricity generation. Moreover, manufacturers in the wind energy sector are constantly trying to improve wind turbines, mainly in the area of wind turbine control and electrical system design, in order to meet the strict grid code requirements.

Other countries: Due to the growing trend of VRE penetration, several countries are paying special attention to grid codes to foster the integration of VRE and to ensure security of supply. Each country proposes their grid codes according to the requirements of its grid and to its own system characteristics. In Italy, one of the requirements is to install data collection systems in wind farms to allow the TSO to monitor the production of connected plants in real time. Given the fact that in Italy wind power has not reached the high levels of penetration as in Denmark, the grid codes in this country are more flexible. In the case of frequency regulation, the wind generators must remain connected but they are not forced to vary their power output when the frequency is between 47.5–51.5 Hz. For countries that are developing their first wind turbines, and for those that are in the process to achieve greater VRE penetration, it is possible to learn from the evolution of grid codes for VRE technologies in other countries that have similar characteristics and that have achieved successfully the integration of wind turbines into the system. In this regard, the collaboration of several countries and regions to harmonise grid codes have strengthened this learning process and facilitates manufacturers to develop standards products; for instance, the European Network System Operators for Electricity (ENTSO-E) has produced a common set of drafts requirements for grid connection where specific values can be assigned for different power systems according to their unique needs and characteristics. When designing or adapting grid codes from other countries, the characteristics of the system such as generation mix, nature of the grid, geographical resource concentration and degree of grid isolation should be considered.

Sources: Energinet, 2008; Sourkounis and Tourou, 2013; IRENA, in press network codes on "Requirements for Generators" (ENTSO-E, 2013). It is important to note that any such learnings need to be updated to reflect the latest available technologies and system operation methods. Furthermore, compliance verification mechanisms, such as inspection and certification, are crucial to the successful use of grid codes.

Forecasting

Forecasting of the resource (wind, solar), as well as the power output of the VRE generation can be a very useful tool for system balancing for the dispatch allocation as well as in cases with centrally planned generation. Multiple forecasts at different time-scales can help improve the reliability of forecasts.

This requires coordination and sharing of expertise and data between the power system operators, national and regional meteorological agencies and individual VRE generators. Agreements for measurement and sharing of power generation data, local meteorological measurement data and meteorological forecast data need to be in place between the individual stakeholders. Power generation forecasting may be centralised, in which case individual generators would be required to report power generation and local meteorological data to system operators, or it could be done by individual VRE owners.

Incentives to increase the accuracy of forecasts may be designed in different ways. In contexts with low VRE penetration, a positive incentive to match generation with forecasts can be provided by a bonus as in the case of Italy. In situations where there is geographically concentrated VRE generation, accurate forecasts can become critical to operation of the power system, and penalisation of large deviations from forecasted generation would have to be considered.

Curtailment

In Europe, between 0.5% and 2.5% of the electricity produced by VRE was curtailed in 2012 (INSIGTH_E, 2014). In the US, curtailment of wind power generation ranged between 0% and 4% in 2013 (NREL, 2014b). In Germany, congestion in the distribution network was the main cause for curtailment, while congestion in the transmission lines was the main problem for wind curtailment in Texas.

At these low levels, curtailment can be a cost-effective strategy to ensure the integration of variable renewable energy, especially when compensation for curtailment is cheaper than investments to alleviate the local congestion (Lew, *et al.*, 2013). Otherwise, curtailment should be seen as an intermediate solution to ensure reliability until other grid integration measures come into effect.

Performance reporting

Real-time monitoring and reporting of VRE output to system operators can be a very useful practice which has already been demonstrated in Denmark, Italy, and Spain (Box 7). It can be used by the system operator for real-time dispatch decisions and to improve forecasting techniques.

It can be also used in combination with remote control ability for downward regulation of VRE generators in extreme cases with high production and low demand, reducing the need for investment in grid infrastructure while minimising generation losses.

Grid connection and access

As a measure to promote and accelerate the deployment of renewables, several countries have legislations in place guaranteeing connection and access to the grid. However, the details of how this is implemented may vary widely. In general, any grid connection policy can benefit from resource assessment and long-term, integrated planning of the power system (see chapter 3) to identify areas with a potentially high number of VRE installations and network reinforcements that needs to avoid overloading of the grid infrastructure.

Administrative procedures and financing structures for grid connection need to be carefully considered. Administrative procedures for project approval and grid connection need to be simplified as shown in the case of Italy and Morocco. This may be more effective in a vertically disintegrated power system, which theoretically provides a level playing field for all generators to network resources.

In any case, financing structures for grid connection can have a significant bearing on VRE deployment. By having well-defined cost-sharing schemes for connection and network (reinforcement) costs to support

Box 6: Forecasting – Australia

Background: Since the first stages in the development of the wind power in South Australia, back in 2001, the regulator recognised the importance of forecasting. As result, the Australian Energy Market Operator supported the development of a centralised forecasting programme for wind power generation through the Australian Wind Energy Forecasting System (AWEFS), which incorporates inputs and integrates collaboration from the whole wind power sector. South Australia had 37.2% of the nation's installed capacity in wind by the end of 2013.

Results: Australia has recognised the importance of forecast systems in order to increase VRE penetration and avoid adverse effect on system security and operation. The Australian market operator realised that having a national forecasting system would be more cost-efficient, accurate and reliable for market operation than funding and operating individual forecasting systems. For this reason a centrally coordinated model (AWEFS) was established to develop and deliver suitable wind forecasts that, together with demand forecasts and individual production profiles, would be fully integrated into the market dispatch and pricing process. These forecasts are used to provide a forward price projections up to seven days ahead and sent to all participants so they can make their own output and commitment decisions. The national wind forecasting system incorporates inputs from weather service providers and wind generators, which are obliged to provide information regarding their availability and their real time SCADA measurements. The outcomes of the system are forecasts for all the wind farms for five timeframes: (1) the dispatch, 5 minutes ahead; (2) 5 minute pre-dispatch, one hour ahead and updated every 5 minutes; (3) Pre-dispatch, up to 40 hours ahead and updated every 30 minutes (10% Probability of Exceedance); (4) Short-term Projected Assessment of System Adequacy (PASA), 7 days ahead and updated every 30 minutes (90% Probability of Exceedance); (5) Medium-term PASA, 2 years ahead and updated every day (90% Probability of Exceedance). Moreover, the design of the forecasting system is such that it can also be used by researchers, institutions or companies to improve the forecasting processes or adapted to other VRE such as solar. The progress in forecasting tools together with the regulatory framework has helped the Australian system to face the rapid growth of wind generation: during the period 2001-2013 there was an average annual rate of growth in installed capacity of 46.6%, mainly in South Australia. For this specific region 28% of its electricity demand was produced by wind power in 2013.

Other countries: Countries aiming to increase their penetration of VRE in the grid can learn from the Australian experience in developing forecasting tools or in designing a regulatory framework that incentivises making more accurate forecasts, especially if they have low levels of interconnection with other grids. Canada implements a centralised wind power forecasting system with a single forecast provider that sends the same valuable information to all the power actors, this information is also used to simulate wind power impacts on system operations. On the other hand, Italy has evolved and adapted its regulatory framework to incorporate developments in energy forecasting systems. Initially, VRE generators were not penalised for the imbalances between forecasts and generation and, as an incentive, a bonus was provided to those VRE generators that correctly forecasted production. However, since 2013 VRE generators were penalised if their imbalances passed a certain threshold (20%), which has been gradually reduced until it completely disappeared in early 2014 to incentivise accurate forecasting that will facilitate the secure operation of the grid with high shares of VRE. Denmark is another example where not only a regulatory framework, but also different actors have played an important role in the development of advance forecasting tools of wind power, although unlike Australia, it was not coordinated in a centralised manner.

Sources: NREL, 2012a; AMEO, 2014; Mereghetti, 2014; Clean Energy Council, 2015

deployment, barriers to VRE integration can be relieved and project sites can be selected more cost-effectively based on market and locational signals.

This problem can be tackled in several ways, depending on where the burden of connection and network costs are placed. This could range from the entire costs being

Box 7: Performance reporting – Spain

Background: Spain is one of the pioneering countries in developing wind energy, which has recently become the fourth largest technology in electricity generation. This rapid growth has forced wind power actors and the TSO to work jointly to develop strategies to address some of the technical challenges to grid security with the penetration of renewable energy on an isolated grid. One of the strategies was the creation of the innovative Control Centre for Renewable Energy (CECRE), where the TSO (REE) monitors and controls renewable energy installations on a real-time basis.

Results: Given that the Spanish system can be treated as a semi-island system due to its limited grid interconnection, it is vulnerable to sudden changes to generation/supply. To counteract these challenges, the system operator (REE) realised the value of controlling the overall production in real-time, especially with VRE generation. In June 2006 REE launched the CECRE with the objective to monitor and control VRE generation, to facilitate its integration while ensuring the security of the system. With CECRE, Spain was the first country to have a unique and dedicated control centre for all the VRE generation units, allowing not only a secure operation of the system, but also a more efficient real-time operation of the power plants. According to the regulatory framework, all those VRE generators with installed capacity greater than 10 MW must be connected to a Renewable Energy Source Control Centre (RESCC) – there are around 28 RESCCs in Spain neither owned nor operated by REE, though in continuous communication with REE sending bi-directional control signals through CECRE. These RESCCs have to be directly connected to the CECRE to exchange real-time data such current state of the units and voltage control capabilities following orders of the TSO. Subsequently, the CECRE sends orders for controlling the power output to RESCCs, who in turn, send the signals to the VRE generators that have to comply with these orders (mainly to reduce production) in less than 15 minutes. CECRE uses a Maximum Admissible Wind Generation tool that according to real-time information determines whether the present generation scenario is acceptable for system operations according to the fault ride-through capabilities of generation plants, congestions on the network and system balance with an appropriate level of downward reserves. CECRE has been a key factor in maximising the VRE integration, while assuring overall security of the Spanish electricity system, making it possible to achieve 27% of installed capacity and 25% of the energy generated from VRE technologies in 2013. Especially as on several occasions, more than 50% of the hourly demand has been met only with wind energy generation, an impressive figure for a country with an isolated grid.

Other countries: Spain is a very good benchmark regarding control tools in real-time to support the integration of VRE in the grid, especially if they have low levels of interconnection with other grids. In fact, system operators and regulators from many countries are constantly visiting CECRE. Other control centres have focused their attention on aspects like reporting state of the units, implementing forecasts very close to real-time and assessment of wind penetration, but CECRE is unique in that it also controls VRE generators remotely in real-time. For instance in the Nord Pool, there is a real-time monitoring of the power flow on the transmission lines between Denmark and the grids in Germany, Sweden and Norway essentially for managing wind generation and therefore Danish wind farms are obliged to report their schedules every 5 minutes. In Ireland the control room has a Wind Security Assessment tool to estimate the maximum amount of wind the system can accept. In 2011 the System Operator in eastern Germany inaugurated a new control centre mainly focused on implementing forecasting tools and near-real-time management.

Sources: CERCE, 2010; Jones, 2012; NREL, 2012a

borne by the generator and then passed on through the consumer through electricity prices (UK), to systems where the generator has to pay for connection to the network, while the network costs are allocated to the consumers (Denmark).

Another problem related to grid connection for generators in remote areas is the risk of suboptimal investment in grid infrastructure, when deployment takes place over a period of time. This may result in unnecessary duplication of transmission infrastructure. However,

Box 8: Grid connection and access – Turkey

Background: During the past few years Turkey's attention regarding renewable energy development policy was mainly focused on wind power. As response to the large number of applications for decentralised wind power connections received since 2007, the regulatory framework has been adapted to accommodate these requests. To manage connection capacity, a unique queue management system was created by the TSO and the regulator, which consists of an auctioning process for wind and solar installations to control the speed of the high up-take rate of renewable energy in the country.

Results: In contrast to most countries where grid connection is guaranteed to all renewable energy projects and the allocation strategies for connection were based on first-in first-served or pro-rata, Turkey launched in 2011, an innovative way to manage the queue of grid connection requests for renewable energy technologies, having delayed both wind and solar applications for three years, while creating this methodology. The objective of this strategy is to efficiently allocate connection rights, while at the same time controlling the high applications for grid connection caused by other incentives such as a FIT. The queue management process for VRE projects consists of the following steps: (1) The TSO publishes the connection conditions and available wind or solar capacity for each substation, taking into account the stability of the current infrastructure. (2) Wind and solar power applications are sent to the regulator (EMRA) and the TSO (TEİAS) to study connection opportunities. (3) EMRA provides the license to the applicant, in the case where there is only a single request for a substation. Otherwise, the TSO instigates an auction to determine the allocation of connection rights. (4) In the auction all the applicants for the same substation send a bid reflecting teir willingness to pay if the license is obtained. The bid is expressed in a fee per kWh, per MW of installed capacity. The applicant with the highest bid wins the auction and the right to connect to the grid. The contribution margin is paid by the winner of the auction to the TSO, in addition to standard connection and grid usage fees. This tendering tool allows the TSO to receive information of both the applicants' willingness to pay to be connected and the regions where the grid needs reinforcements to introduce more renewable energy. Other grid-related regulatory tools in Turkey are the priority of connection for renewable energy over conventional technologies, licenses are open to other renewable energy technologies different from solar and wind, a significant deduction (up to 85%) in system usage tariffs for the first 5 years and an exemption from paying an annual license for the first 8 years. The strategy taken in Turkey not only prioritises the connection and deployment of VRE, but also promotes the security and reinforcement of the grid that will help to further integrate VRE.

Other countries: In most of the countries when the development of VRE is in the initial stage, grid connections are allowed for all renewable energy projects, however, when the level of penetration of VRE rockets, new strategies to manage new connections are required to guarantee security of the system. The auction system implemented in Turkey is a good case study for countries that want to increase the integration of VRE, while being consistent with grid security. Other options to support grid integration are deep tariff mechanisms, in which grid users have to pay tariffs for connection, construction and reinforcement, this is the case of Hungary where the DSOs/TSO are obliged to connect renewable energy plants even if that means expansion or reinforcement of the grid. In Italy renewable energy technologies have priority of connection even if expansion of the grid is required, in such a case the costs are borne by the system operator. Italy implements a simplified procedure to control connection applications by charging an application fee (30% of the connection cost).

Sources: TEIAS, 2012; ECRB, 2013

efficient investment in network extension is hindered by the risk of stranding of connections in the absence of proactive deployment (World Bank, 2013) in which grid infrastructure is developed in anticipation, and in order to guide deployment, of VRE projects. Mechanisms to share the risk of investments in network extensions (Australia) have the potential to help relieve this barrier (Hasan, *et al.*, 2013).

Table 6: Relevance of VRE grid integration measures for system operators

Measure	Stakeholder engagement	Data needs	Flexibility conditions	Technology
Nodal pricing for congestion Management	Generator; System operator; Regulator	Power flow data; Resource mapping; Network planning and modelling	Concentration of VRE; Limited VRE portfolio; Constrained grids; Limited interconnection; Inflexible demand	FACTS; Synchrophasors; Distribution automation; Dynamic line rating
Incentives for investments	Generator; System operator; Finance sector	Capacity and network planning and modelling	Weak grids; Limited interconnection; Limited operational capabilities; Limited investment opportunities	
Integrated network Expansion	System operator; Regulator; Energy planner	Power flow data; Network planning and modelling	Weak grids; Limited interconnection; Limited operational capabilities	HV AC/DC lines; Interconnectors
Public engagement	System operator; Regulator; Energy planner; NGOs; Consumer	Capacity and network planning and modelling; Resource mapping	Weak grids; Limited interconnection; Limited operational capabilities; Inflexible demand	Underground HVDC lines; Advanced metering; Advanced electricity pricing
Reliability reporting	Generator; System operator; Regulator	Generation and power flow data; Resource mapping	Weak grids; Limited interconnection; Limited operational capabilities	Smart inverters

6.2 VRE grid integration measures for system operators

There are five VRE grid integration measures that are relevant for system operators. As discussed in chapter 3, an integrated network expansion plan focused on minimising total system costs, can ease a transition towards renewable power generation from an early stage. Public engagement should coincide with the development of the network. New operational procedures like nodal pricing and tradable transmission rights can be used to increase the effectiveness of the network as VRE shares increase.

Nodal pricing for congestion management

With an increasing share of VRE in power systems, interconnectors and transmission lines are expected to play a bigger role in dealing with regional imbalances. However, several factors contribute to determining their effectiveness in power balancing. These include the physical power transmission capacity of the lines, and the level of coordination in determining imbalances and allocation of this capacity between the two balancing regions.

Congestion prevents the most cost-effective set of generation resources from being available. It is one of the drivers for investments in transmission infrastructure in the long term. However, in the short term, the existing transmission lines need to be managed in cases of congestion to ensure reliability, and in certain cases it may be even more economical to allow this to happen, as opposed to eliminating all congestion by increasing transmission capacity (IEA, 2013). However, this needs to be done in an economically efficient manner.

This can be done by having nodal pricing (or locational marginal pricing (LMP)) in power markets with gate closing times closer to production. This system allows prices to differ at different points in the power grid. It takes into account the fact that excess supply may not be able to serve additional demand due to local congestion constraints. A market for tradable transmission rights can lead to efficient allocation of infrastructure to market participants by incorporating the cost of network use to the marginal cost of production of electricity. Application of this system to generators (including VRE generators) can provide incentives to produce power in response to the practically available demand in the short term, reducing the need for inefficient centrally administered dispatch schedules or curtailment measures. In the long term, it can provide location signals for the siting of new generation capacity in response to the availability of transmission capacity.

However, this approach requires constant monitoring and transparent communication of data to all market participants. The costs and benefits of such an approach would need to be evaluated on a case-by-case basis. Zonal pricing has been implemented in several regions (Nord Pool Market, Italy), which is a version of nodal pricing in which prices are allowed to vary between larger zones.

Incentive for Investments

System operators are often conservative while making investments in new technologies or expansion projects. This may be due to high uncertainty associated with the performance and returns of new technologies in a specific system or application. Often, even technologies with demonstrated cost savings may not be deployed because of additional efforts needed to acquire new skills or adopt new procedures required for the technology. Smart grid technologies often not only enhance existing services delivered by the system operator, but create new services as well. This creates barriers for desirable changes aimed at increasing efficiency and flexibility in the power system.

Financial incentives such as policies, which reward greater operation flexibility, or a greater rate of return on certain grid technological investments for regulated utilities, could be employed. The information produced using smart grid technologies can be valuable in a more directed delivery of energy services, and as such, can potentially be attractive for investments from private sector actors, such as energy service providers and aggregators, especially in the distribution grid.

Integrated network planning

One of the main features is the increased requirement for coordination at several levels through integrated network planning. Coordination between new generation and grid upgrading and expansion will need to be adjusted to account for the mismatch between lead times for VRE and grid infrastructure projects. This would also have implications for planning at the local and regional/national level. While planning and expansion of grid and generation capacity may be done by planning authorities at a local level, it also needs to be done within the larger framework of wide-area development. Central bodies for integrated top-down planning need to play a bigger role in identifying potential synergies in neighbouring operating systems and aligning local benefits with it. This also calls for increased efforts to remove administrative barriers for projects spanning more than one jurisdiction. Well-defined agreements for project planning and execution between grid owners and operators in neighbouring areas would need to be in place to ensure that network development can keep pace with VRE deployment.

Public engagement

Renewable energy and transmission network projects can face barriers in the form of problems related to land acquisition, especially in densely populated or environmentally sensitive areas. While transmission planning with environmental assessment is essential, health, land use change and aesthetic concerns may also have to be addressed in such projects. This needs to be done while engaging the relevant stakeholders such as citizens, experts, environmental associations and public interest groups from an early stage in the planning process. By having transparency in the planning process with indications of costs and benefits of different alternatives, and well defined procedures to address concerns through public participation, delays during advanced stages of project development can be avoided. Systems promoting community-based ownership of VRE generation can help increase acceptability while allowing the public to benefit directly from power generation, and hence, making them stakeholders in ensuring increased deployment and integration of VRE (*i.e.* Denmark).

Reliability reporting

A major gap obstructing the assessment and prescription of grid integration measures is the absence of

Box 9: Congestion management – New Zealand

Background: Insufficient network capacity and congestion problems are main obstacles for VRE integration. One of the most interesting mechanisms to manage congestion is by using a nodal pricing mechanism, as is the case for New Zealand. Nodal pricing consists of a bid based Security Constrained Economic Dispatch (SCED) model that leads to an optimal (least costly) dispatch to meet the demand, while taking into account the technical constraints of the grid; the result is that each node of the grid has a different price responding to the conditions of the system (generation, demand and grid). In other words, nodal pricing allows for managing the congestion within the market.

Results: New Zealand is a special case, as its isolated location does not allow congestions to be solved through interconnections. New Zealand experiences grid congestion, and therefore an efficient congestion management mechanism is required: one of the most important lines, a 350 kV HVDC link connecting the north and south islands, is congested 0.5% of the time; another inner line of northern island, where most of the demand is located, is congested 9.3% of the time; other important lines are occasionally congested. New Zealand Electricity Market (NZEM) has been operating a nodal scheme since 1996. The scheme consists of 244 nodes, electricity trading periods of 30 minutes and around 80% of all electricity consumption is traded through the NZEM, although much of it is hedged with Financial Transmission Rights (FTR) – an instrument to hedge the risk of congestion and its impact on variability of nodal prices. The nodal pricing mechanism is an optimal solution for congestion management and efficient use of the grid, in contrast with other out-side-the-market mechanisms with inefficient and costly curtailments, such as in those markets where the grid is not considered for clearing the market (single node approach) and the congestions that are solved in an ex-post procedure by curtailing some units and committing others. The efficient management of congestion and additional capacity is a key element for large scale renewable energy integration. Moreover, nodal pricing provides information about the current state of the grid, informing the system operator where the network needs to be reinforced and gives signals to the generators where to locate themselves in the long-run and how to programme their schedule and bids in the short-run according to the state of the grid. This means that new generators, including VRE generators, will base their siting decision not only on the location of their energy sources, but also where nodal prices are higher, which is usually closer to the load centres. It also helps to relieve congestion in some areas. This behaviour is clearly seen in New Zealand where around three quarters of the installed capacity of hydro, installed before the implementation of nodal pricing, is located in the south island where most of the hydro resources are, creating a congestion in the lines because most of the demand is in the north island (around two thirds of total demand). However, the implementation of nodal prices led generators to install the plants in the north where nodal prices are higher, *e.g.* most of the thermal plants are located in the north island. Regarding VRE generation, even though there are favourable conditions for wind generation all over New Zealand, most of the wind farms are located in northern island where nodal prices are higher and therefore help to alleviate possible congestions. Wind generation represent 5% of New Zealand energy supply with more than 670 MW capacity installed.

Other countries: There are other experiences of nodal pricing such as in the US (PJM, ERCOT, NYSO) or zonal pricing in the Nord Pool and Australia. The implementation of zonal pricing in Australia has achieved similar results as in New Zealand, making wind generators to be installed near load centres rather than where there is more wind potential and therefore helps to relieve congestion. Mexico is a special case where there is not a liberalised market and the dispatch and unit commitment is done with a SCED model taking into consideration all the nodes and managing congestion optimally.

Sources: NZEM Rules Committee, 2002; Kelly, 2011; Mathiesen, 2011

comprehensive and consistent data on power outages and grid reliability (Whited, Woolf, and Napolean, 2015).

In the absence of requirements for system operators (especially DSOs) to report such data, the impact of

VRE and the performance of the power system in a specific context may become difficult to assess. This is true especially in regions with developing grid infrastructures, where grid infrastructure has to be expanded to meet growing demand, and in regions with favourable policies leading to high deployment of variable renewables. Even in regions without these characteristics, the absence of consistent measures of performance and reliability makes it very difficult to compare these effects across different cases.

6.3 VRE grid integration measures for the demand side

With increasing shares of VRE, the demand side is becoming a more important player to ensure the balancing of the grid. A number of measures, like demand side management and reliability reporting, are cost-effective without high penetration levels of VRE. On the other hand, new tariff structures and business models will becoming increasingly important as VRE shares rise.

New models for self-consumption

VRE allows consumers to produce their own electricity, and reduce the amount of electricity consumption through the grid (IEA-RETD, 2014; RMI, HOMER Energy, 2015). Changes in business models of traditional utilities may also become necessary in this changed environment. New business models such as co-ownership models for distributed generation and energy storage, shared-savings energy efficiency programmes, etc. need to be considered. Timelines for market integration of grid feed-in from distributed generators would also need to be set.

With the rise of distributed energy resources, "aggregators" are likely to play a big role in incorporating them into the power system, especially in developing power systems (Gordijn and Akkermans, 2007). By aggregating distributed generation, storage and/or loads, they can be enabled to participate in the wholesale market and plan self-consumption and shift loads in a way which is the most economical to the customers, or provides balancing

Table 7: Relevance of VRE grid integration measures for the demand side

Measure	Stakeholder engagement	Data needs	Flexibility conditions	Technology
New models for self-consumption	Consumers; Electricity suppliers; Aggregators; Regulator; System operator	Resource mapping; Generation, demand and power flow data; Capacity planning	Low generation flexibility; Distributed VRE; Weak distribution networks; Limited operational capabilities; Limited investment opportunities; Inflexible demand	Distributed battery and EV management; virtual power plants; Distributed heat/cold storage; Advanced metering
New tariff structures	Consumers; Electricity suppliers; Regulator; NGOs	Generation, demand and power flow data; Capacity planning	Distributed VRE; Weak distribution networks; Inflexible demand	Distributed battery and EV management; Demand response; Advanced metering; Advanced electricity pricing
Demand side management	Generator; System operator; Regulator; Consumer; Energy planner	Generation, demand and power flow data; Capacity planning	Low generation flexibility; Weak grids; Inflexible demand;	Distributed storage technologies; Advanced metering; Advanced electricity pricing

services in the control power market. The viability of such business models and its dependence on factors such as demand profile, load characteristics and distributed generation portfolio needs to be further evaluated.

New tariff structures

Traditionally, consumer electricity prices reflect the generation costs, the network costs, the operational expenditure of suppliers, and taxes or levies. The tariffs may differ depending on the consumer (industry or residential), the amount of electricity consumed, and (sometimes) on the location of the consumer. The tariff may also be based on social criteria, such as ensuring that all customers can access and afford electricity. However, they mostly do not reflect the underlying variability in wholesale prices and network costs required to ensure that supply matches demand at all times.

VRE together with recent trends involving increased self-consumption from grid connected distributed generation, smart meters, demand side management for peak load shifting, and energy efficiency measures may require new tariff structures to reflect the changes in the generation mix, network and system operating costs. These adjustments can take place at different levels. In particular, the network charges may have to adapt to reflect VRE grid connection costs and to reflect consumers efforts to reduce peak load. Furthermore, time-varying rates reflecting peak demand (or a mismatch between supply and demand) can be used to create flatter energy demand profile, requiring lesser investments in power generation infrastructure to cater to peak demand. Distributed storage options are accelerating the need for real-time pricing (Favuzza, *et al.*, 2015). The use of market-based mechanisms in combination with advanced metering to develop time-of-use tariffs or locational dynamic pricing can be considered

Smart systems can support time-varying rates. Smart meters, remote fault detection, isolation and restoration (FDIR) systems, distribution automation and active management to create cost reductions in network operation and management, grid upgrades, customer care, billing, etc. (Dupont, *et al.*, 2014; The Brattle Group, 2015). In cases with high VRE penetration, when used in combination with demand and generation forecasting, and system monitoring to identify transmission bottlenecks, variable pricing mechanisms can help relieve congestion and can guide energy consumption in response to prices driven by VRE generation.

Demand Side Management

Effective demand side management in a power system can serve many purposes. Demand response has traditionally been used to manage large, predictable commercial loads, because annual peak demand shifting can reduce the requirement for installed capacity of peak plants, which may run only for a few hours in a year. More recently, it has also been used to reduce load during periods with high wholesale electricity prices or when renewable output reduces (Shariatzadeh, Mandal, and Srivastava, 2015).

However, there is increasing experience in using demand response to smooth volatility and provide ancillary services in the face of increasing VRE shares, such as non-spinning reserves, spinning reserves, flexible capacity ramping and regulation services (Morales, *et al.*, 2015). Furthermore, direct load control, contracts for interruptible loads and residential water-based thermal energy storage systems for load shifting have already been implemented in a number of power systems. However, its social acceptability and effectiveness needs to be ensured by providing price data in advance to consumers, and communication the implications of advanced pricing clearly before and during implementation.

6.4 VRE grid integration measures for regulators

In cases where VRE technologies have matured sufficiently and costs may have been lowered to a level such that it reaches market parity, measures may be taken to help shift VRE production and deployment to take place in more flexible ways (Cochran, Katz, and Miller, 2015). This measures may include the removal of floor prices (allowing for negative electricity prices (in the case of Denmark), or the option to shift from subsidised generation to market based production with an additional market premium such as in Germany. Improvements in technology have also opened the possibility of VRE generators participating in ancillary markets, which may be economically advantageous as compared to other measures in many cases (NREL, 2014a). However, this may not necessarily reduce the need for upward regulation or reserve capacity.

Box 10: New tariff structures – Vanuatu

Background: The Utilities Regulatory Authority (URA) in Vanuatu has developed an innovative tariff structure to support VRE integration, in place since 1st of October 2014. The objective is to promote the implementation of small-scale solar energy connected to the grid with a feed-in and net-metering programme to allow consumers to manage their own consumption and promote a share of renewable energy. The way the tariff system is designed and implemented is a critical aspect of an effective renewable energy integration into the system. Before this initiative Vanuatu did not have any regulation in place regarding grid-connected solar home systems (SHS).

Results: Vanuatu has launched a National Energy Road Map (NERM) with specific targets for renewable energy utilisation, *i.e.* a share of 40% renewable energy generation by 2015 and 65% by 2020. To support this target, a programme has been established with initial plans for an installed capacity of 320 kilowatt-peak (kWp) for domestic customers, 120 kWp for commercial customers and 60 kWp for industrial customers. The programme has two metering methods: a net-metering method directed to domestic customers and a Bi-directional metering for commercial and industrial customers. In the net-metering scheme customers consume from their own generation or from the grid in case it is needed, the excess of electricity produced is injected to the grid and the consumer will be charged only for its net consumption (kWh consumed minus kWh delivered to the network). The meter is provided by the utility. The consumption charge for the net consumption is USD 0.67/kWh, the fixed charge is USD 2.76/KVA and an access fee, according to the size of the SHS, of USD 12.15/KWp is applied to compensate for the network use. In case of more electricity sent to the grid than drawn from it, the net injected electricity shall offset the fixed charge and the access fee at a rate of USD 0.13/KWh. In case there is electricity fed-in in excess of that which offsets the fixed charge and access fee, it shall be fed-in for free, *i.e.* there are no negative bills. The bi-directional method separately measures electricity drawn from the network and energy injected to the network. The total amount of electricity taken from the grid over the billing period is charged at a retail tariff of USD 0.49/KWh for commercial consumers and USD 0.38/KWh for industrial consumers. The fixed charge is USD 11/KVA for commercial consumers and USD 13.83/KVA for industrial consumers and there is no access fee. The price paid for the electricity fed-in to the grid is the feed-in tariff (USD 0.21/KWh). As there is no negative bills, the energy fed-in to the grid, valued according to the feed-in tariff, can be used to offset the fixed charge and the consumption charge, any additional energy injected to the grid shall be fed-in for free. The Access Fee introduced in the programme for those customers using SHS with net-metering will tackle the possible cross-subsidy between customers in the program and those that are out the programme. This programme and its tariff structure not only fosters the integration of VRE but also empowers customers to manage their electricity expenses benefiting from self-consumption, changes the business model of the utility (UNELCO) by reducing revenue in some aspects and creating new revenue channels in other aspects. Moreover, this programme creates new benefits for the use of the grid and reduction in generation investment costs.

Other countries: Vanuatu's pioneering tariff structure to support the integration of renewable energy is an interesting case study that can be assessed and adopted by other countries. There are other examples of islands modifying their tariff structure to support the integration of renewable energy. Tonga uses a bi-directional connected system that allows customers to use their own generation and feed any excess to the grid at no charge and there is no access fee. Other islands such as Grenada, Seychelles and Ramea Island set the payment of energy fed-in to the grid linked to avoided fuel costs. In 2009, Italy evolved its net metering scheme from physical to economical compensation, *i.e.* Scambio Sul Posto (SSP). In this new scheme the cost of electricity (COE) consumed is calculated and compared to the value of electricity (VOE) fed-in to the grid by the IPPs, which is calculated with an hourly zonal price mechanism. When VOE is greater than COE, the IPP is compensated with an economic credit that can be used to buy electricity in the future or paid yearly. Under the SSP scheme the electric system operates as a virtual energy storage for electricity produced but not consumed in the same period.

Source: URA, 2014.

Box 11: Demand side management – Republic of Korea

Background: Due to the dramatic growth in both electricity consumption in South Korea in the last decades and the difficulty to finance and build new power plants within a short period of time, DSM policies became a priority to stabilise the system. South Korea has realised the benefits of DSM programmes not only in peak shaving and reducing energy consumption and costs, but also in reducing uncertainties from the demand side and increase the flexibility and reliability of the system, and hence facilitating the integration of VRE.

Results: Korea is one of the countries that has implemented and actively operated DSM strategies, achieving outstanding results since 1970's. These programmes had been implemented by KEPCO (Korean utility in charge of the transmission and distribution) and the government. There are several DSM programmes in place that can be divided in two big groups: Load Management and Energy Efficiency Improvement. Load management have three main targets, which are Load Reduction (reduction of peak demand), Load Shifting (moving from peak demand to fill up valley hours) and Emergency Programmes (monetary payments for customers who reduce their pledged loads when requested by KEPCO). Load Reduction consists of three sub programmes: (1) Demand Adjustment programme of Designated Period, which offers subsidies for customers who reduce their peak consumption during the summer on-peak periods (10-20 days) that is announced 6 weeks in advance by KEPCO - subsidies between USD 0.76 - 0.93 per peak demand reduction (kW) in 2010; (2) Demand Adjustment programme of Advance Notice, which offers financial incentives to customers who reduce their demands at any peak time for at least half hour and save their electricity price, the peak time is regardless the season and is announced between 1 and 7 days in advance by KEPCO - incentives between USD 0.36 - 0.57 per load reduction for 30 min (kW) in 2010; and (3) Demand Resource Market, which was opened in 2008 by KPX (Korea Power Exchange) to control the load at critical times when operation reserves are predicted to be below 5 GW or when yearly peak demand occurs. The scheme is ruled by market principles (prices and load reduction bids submitted by market participants) and operated either by forward market or spot market. Regarding Load Shifting the main sub programmes are Cool Storage System, which stores heat in the cool storage medium during the off-peak period and is used during peak periods for air-conditioning, and time-of-use tariffs (TOU). The Emergency Load sub programmes are Emergency Voluntary Load Reduction, Direct Load Interruption and Emergency Load Reduction, all have to be notified at least 1 hour ahead. Finally, Energy Efficiency are in place by KEPCO and are tackled with high efficient lighting, inverter and electric chiller. These solid DSM strategies have led Korea to achieve the world's highest load factor level until 2011 (77.6 % in 2010, 4.5% was improved by DSM), to reduce the peak demand by 3.3 MW in 2010 and to achieve a stable power supply. This stable system, its flexibility and the expertise in DSM has allowed Korea to look for higher penetration of VRE through the implementation of smart grids, where DSM is a key element, as it can be evidenced in the smart grid test-bed in Jeju Island.

Other countries: There are important aspects that can be learnt or adopted from the diverse DSM strategies implemented in South Korea, especially to assess the potential use of load management, as an alternative to supply management, to balance the system and make it more flexible to facilitate the introduction of VRE. Incentivised mainly by the wide deployment of smart grids, several countries have implemented or updated new DSM policies. In China an Industrial DSM programme is in place that achieved 50 MW reduction in peak demand and an improvement in the load factor due to the increase in consumption during valley hours. In Texas (US), there is an advanced DSM programme that allows industrial loads to participate into ancillary service market. However, active DSM programmes are still needed for the commercial and residential customers.

Sources: KEPCO, 2011; Kwon, Lim, and Song, 2014

There are number of design features that can be used to support the integration of variable renewables, which impact stakeholders in the power sector from generation to system operations to consumption. As such, the regulators play an important role and in general their relevance increases as the share of VRE rises.

Table 8: Relevance of VRE grid integration measures for regulators

Measure	Stakeholder engagement	Data needs	Flexibility conditions	Technology
Sub-hourly scheduling and power markets	VRE generator, System operator; Regulator; Financer	Generation, flow and demand data; Capacity planning; Resource assessments	Inflexibility dispatchable generation; Limited operational capabilities; Long dispatch intervals	Flexibility upgrades; Virtual power plants; controllable VRE
Control power markets and procurement	Generator; Regulator	Capacity planning; Generation, flow and demand data; Resource mapping	Competitive power markets, low generation flexibility	Controllable VRE; Flexibility upgrades; Virtual power plants; Pumped-storage hydro; Distributed battery; Forecasting; Direct load control
Ensuring capacity adequacy	Generator; Consumer; Regulator	Capacity planning; Generation, flow and demand data; Resource mapping	Liberalised power sector, developing/ aging infrastructure	Controllable VRE; Reserve Capacity; Pumped-storage hydro; Distributed battery
Market integration and cooperation	Regulators; Planning bodies; TSOs; Generators	Capacity and network planning; Generation, flow and demand data; Resource mapping	Interconnected power systems, complementary generation/storage resources	HV AC/DC lines; Interconnectors
Data ownership rights	Regulators; Planning bodies; Generators; Consumers; Energy service companies; ICT companies; Car companies	Power flow and demand data	Competitive power markets	Smart meters; Distribution automation; Distributed battery and EV management; Virtual power plants; Direct load control

Sub-hourly scheduling and power markets

To guide economical investments in VRE, markets need to be designed with short gate closing time in multi-settlement systems (an example is the Nord pool). This includes day ahead scheduling (or markets) in which the bulk of power trading is done, and intraday scheduling (or markets) in which actors can trade themselves into balance based on more accurate production forecasts and schedules.

In markets, there is a need to maintain financial accountability to adhere to production schedule. The level of compensation/penalties for deviations from scheduled dispatch needs to be carefully decided as this provides incentive to improve reliability, increases predictability and motivates VRE generators to make more accurate forecasts in cases where they have market based dispatch. As an example, imbalance payments in the Nordic market need to be made by producers only when their imbalance is in the same direction as that of the net system imbalance, and the payment reflects the balancing cost at that point in time.

Allowing electricity prices to go negative can also be effective in certain cases. For example, in markets with a floor price set at zero, it may make more economic sense for generators to keep producing power (rather than stopping production) even if they do not get paid. Generators governed by feed-in tariffs or power purchase agreements may be incentivised by feed-in premiums coupled to market prices or time-of-delivery structured PPAs to respond more flexible.

Control power markets and procurement

The design of control power markets is very important to give incentive to conventional and VRE generators to provide balancing power. The requirement for reserve power depends not only on the share of variable renewables, but also on several factors such as generation and load forecast errors and plant outages (Hirth and Ziegenhagen, 2013). By having a wider operational area, the requirement for reserve power can be reduced. There is work being done to develop new methods to determine the optimum required reserve capacity and to procure it. These include dynamic methods in which procurement is done based on power demand and VRE generation conditions on the next day, and price-elastic methods in which procurement of reserves is done depending on price of procurement. Energy storage is another technological option available to provide control power.

With technical improvements in VRE technology, generators, especially wind power, can play a greater role in providing control power. Certain studies also indicate potential for cost savings in cases where wind is allowed to provide regulation power, in addition to reducing wear and tear of other generation assets (NREL, 2014a). However, conditions which enable them to do so need to be created. In vertically integrated systems, this can be done through procurement processes.

Measures would have to be taken to remove barriers to entry for VRE generators and other non-traditional stakeholders into control power markets. In cases with auctions, smaller minimum bids can allow more participation from typically smaller scale VRE producers. Allowing pooling of generators for bids in the market can also help achieve this. In addition, because of uncertainty in VRE generation over longer time-scales, shorter dispatch intervals and capacity commitment periods can allow VRE to participate in control power markets.

Ensuring capacity adequacy

Besides short-term power markets (including control power markets), it is necessary to ensure generation adequacy for peak demand both in the short- and the long-term. There are different ways that capacity adequacy can be ensured. For example, the Californian Public Utilities Commission has obliged smaller load-serving entities to purchase a targeted energy storage capacity equivalent to 1% of peak load by 2020 (IRENA, 2015e).

Well-designed capacity markets is one way to ensure adequacy. They provide payments to owners of generation capacity to keep their capacity available in case price signals through the power markets fail to do so (Cramton and Ockenfels, 2012). However, one must be very careful while designing such markets, making sure that the objectives are very clear, compensation is done in a way that ensures adequacy, and does not lead to overcompensation (Milligan, *et al.*, 2012). Due to the potential impacts of market design on the effectiveness of this market, the German government has decided to introduce a "capacity reserve" rather than a capacity market (BMWi, 2015).

Critics of capacity markets argue that simply adding capacity may actually limit market integration, and that instead 'capability-based' markets should be pursued. From this perspective, other incentives like demand side response or storage technologies are equally or even better suited to provide capacity adequacy (ECF, 2012).

Market integration and cooperation

According to studies, the requirement for regulation reserves reduces with increase in footprint of operational area (NREL, 2012). While there is precedent for cooperation among balancing areas to exploit the benefits of geographical smoothing, cooperation for the purpose of integrating VRE is a relatively new phenomenon (IRENA, 2015h). However, there are instances of studies being carried out to evaluate the benefits of balancing area cooperation (Lew, *et al.*, 2010) and cases where this already being implemented in several areas with high VRE penetrations (IGCC, Nord Pool). The integration of control markets over large geographic areas requires administrative measures, such as energy and balancing market co-optimisation and operating reserve demand

Box 12: Market based renewable energy dispatch – Germany

Background: Germany is one of the countries that have taken the lead in the development and integration of VRE technologies into the power sector, lowering the costs and reaching high deployment levels that allows the regulatory framework to adapt the electricity market design to operate these technologies in response to market forces. The German Renewable Act (EER) has established several market-based instrument that supported the integration of renewable energy to the system. In 2015, the German government proposed a new electricity market design 2.0 to continue to support increasing VRE shares through a liberalised market.

Results: Initially, when deployment levels of VRE were still low, the development of VRE in Germany was supported with two instruments that were not completely market-related: the Feed-in Tariff (FIT) and priority of dispatch. Meaning that all the electricity that was produced by VRE had to be bought directly by the system operator at a generation cost-based rate (FIT) and sold directly to suppliers, even if that meant base-load plants such as nuclear had to ramp down. However, this changed in 2012 into a market-based dispatch instruments when VRE generators could choose a Feed-in Premium option. The premium consists of an extra fixed remuneration on top of the spot market price. The objectives of this instrument is to support the integration of the VRE by encouraging them to sell directly into the wholesale market, stimulates the learning process of VRE technologies with regard to the electricity market and make their generation decision more demand-responsive. The introduction of negative prices is another market design adjustment that was introduced by Germany to support the growing penetration of VRE in to the system and to encourage VRE technologies to integrate and adapt to the electricity market. The rationale behind negative prices is, contrary to arbitrary curtailment, to provide an efficient economic signal to reduce output during excess generation and encourage VRE to adjust their production responding to system needs. Moreover, Germany has also applied another market-related strategy that supports the safety of the system and hence facilitates further integration of VRE; this is the expansion of markets where generators can participate. As generators can participate in different power exchange markets it allows the system operator to deal with the variability of renewable energy by relying on the support provided by interconnections. As it is evidenced with the German case, once VRE technologies have reached certain level of penetration, there are market-based instruments that can be implemented not only to supports their deployment, but also to encourage participants to be more ready to respond to market needs and help in maintaining the security of the system. The proposed electricity market design 2.0 consists of even stronger market mechanisms, more flexible and efficient electricity supply, and a 'capacity reserve' to ensure additional security in case supply does not cover demand at a particular time.

Other countries: Countries can design or adapt some market-based instruments to promote VRE penetration according to their specific characteristics, especially at high penetration levels of VRE technologies. There are several countries that, after having reached large penetration of VRE technologies, have implemented different market-based instruments to help its deployment. Spain, similarly to Germany, started with FIT, which after some years evolved to feed-in premiums to encourage the integration of VRE generators into the power market. Denmark, guided by its experience in growing levels of wind energy, have implemented a large and diverse range of market-based instruments such as feed-in premiums, negative prices, expanded markets and fast market operations (gate closure close to real-time), the last is a very important feature to increase flexibility of the market and therefore facilitates the integration of VRE and reduces the chances of these generators to pay balancing cost. Australia is an interesting case because, besides having negative prices and fast markets, it was the first country to have a National Renewable Energy Market using Tradable Certificates, a market-based instrument to promote generation through renewable sources.

Sources: Fulton, M.; Capalino, R., 2012; NREL, 2012; BMWi, 2015

Box 13: Capacity market – Colombia

Background: Highly dependent on hydro-generation (79% of generation, 2013), it is necessary for the Colombian power sector to have enough generation plants with firm energy when hydro resources are not sufficient to cover the demand, for instance during dry periods like the "El Niño" phenomena, in order to guarantee system adequacy. In a liberalised power sector like in Colombia, where the generation activity and the investment decisions are open to market forces, the solution to guarantee reliability was to create an innovative capacity market, denominated Reliability Charge, to provide long-term signals to encourage expansion of the installed capacity.

Results: In 2006 the CREG (Colombian Energy Regulatory body) designed a market-based mechanism called Reliability Charge that provides long-term economic signals to promote the investment in generation mix expansion, while ensuring reliable energy supply to the system at efficient prices, ensuring that prices do not skyrocket during hydric shortage periods. One of the most important components of this mechanism is the creation of Firm Energy Obligation (OEF), which is a generators' commitment to hedge the energy price during critical scarcity periods. This obligation goes into effect when the spot price overpasses a threshold previously established by the CREG (Scarcity Price). The capacity market mechanism works as a Descending Clock Auction in order to allocate the required OEF to meet the demand among all the generators that fulfil the requirements (both existing units and new entrants) and to determine the Reliability Charge to compensate them. The auction is carried out as follows: first, the CREG determines the total OEF required to meet the demand and expresses it as price-quantity curve. In parallel, the generators that comply with the requirements to participate in the auction (initially hydro and thermal) determine their own OEF and offer a financial value into the auction according to their technology and specifications. The auctioneer begins with a high asking price and based on the bids sent by the generators an aggregated supply curve is built. If there is excess of supply offered for the given price, in the next round the price is decreased and new bids are sent to build a new supply curve. This is done until the generators still willing to receive the announced price meet exactly the total OEF and the last announced price (per KWh) is the Reliability Charge. The generators that were allocated with a given OEF by the auction receive the Reliability Charge, which is a stable remuneration during a given period of time (up to 20 years). In return, these generators are committed to generate and fulfil their OEF when the spot price exceeds the Scarcity Price, which is the maximum price at which this energy will be paid. Regarding renewable energy, the CREG complemented the Reliability Charge mechanism with the inclusion of biomass technology in 2008 and in 2011 defined the OEF for wind power plants to be between 6% - 7.3% of the net effective capacity, considerably lower than other technologies due to the lack of historic data and variability of the technology. In 2015, CREG issued new regulation to take into account the historic data of new wind power plants. This methodology allows wind power plants to participate in the Reliability Charge scheme, creating a new market for this technology and, therefore, provides incentives for wind integration.

Other countries: Regarding integration of VRE, this mechanism is an interesting case study that leads to a more reliable and robust system, making it better prepared to manage greater variability. In addition, it also provides other source of revenue to renewable energy technologies by allowing them to participate in an alternative market. Brazil, inspired by the Colombian mechanism, created separate auctions for existing units and new entrants and defined two separate reliability products: a forward financial energy contract for hydro units and a Reliability Charge for thermal units. The UK has also introduced capacity market based on a pay-as-clear auction which provides a steady payment for capacity in return for a commitment to deliver energy when required, though it is not yet in place. Germany, on the other hand, is proposing a 'capacity reserve' instead of a 'capacity market' thus relying on the electricity market itself to provide sufficient capacity.

Sources: CREG, 2011; CREG, 2015

Box 14: Market integration and cooperation – Gulf Cooperation Council

Background: The six Member States (MS) of the Gulf Cooperation Council (GCC) – Kuwait, Saudi Arabia, Bahrain, Qatar, United Arab Emirates and Oman – decided to interconnect their power systems to reduce reserve requirements and increase reliability while facing a growing demand for power from rapid population, commercial and industrial growth in the region. Moreover, this interconnection is seeking to develop the energy market in the Gulf and to facilitate the integration of VRE, which has already seen by GCC as an alternative to meet rising demand and, at the same time, lessen the local consumption of oil and gas.

Results: The Governments of the GCC countries established the GCC Interconnection Authority (GCCIA) to construct and operate a 400 kV backbone grid connecting the six MS. The interconnection between the GCC countries power systems started operations in 2009 connecting initially four MS and was finally completed in 2011 connecting all the MS. The GCC control centre is located in Ghunan, Saudi Arabia. The project of interconnecting the region has several technical, economic and environmental benefits. The original reason for the creation of the GCC power interconnection was to allow MS to share generating reserves, resulting in savings in generating capacity and to minimise overall investment in peaking plants while still meeting the demand with the same (or better) level of reliability and security of supply – *e.g.* diminishing incidents of blackouts. In addition, the interconnection enables systems to share spinning reserves so that each system can carry less spinning reserve. In sum, it allows assistance from neighbouring systems (energy exchange) to overcome unforeseen imbalances in the short-run or demand growth in the long-run. Regarding the economic benefits, the interconnection brings considerable savings in investments in new generation capacity due to the better utilisation of operating reserves and the support of neighbouring systems. Secondly, the possibility of developing a trade power market not only helps for the progress of the power sector in the region, but also increases considerably the liquidity of the sector. Finally, having a broader balancing area by integrating several systems facilitates the entry of new technologies such as VRE. Given the fact that the GCC region is highly reliant on hydrocarbon fuels for power generation, the integration of VRE is not only beneficial for expanding the generation mix and meeting the growing demand, but it also allows to substitute oil and gas generation by VRE, which means savings in local consumption of oil and gas and, instead, export them to increase Member States' income. In terms of environmental benefits, the balancing area operated by GCCIA – which has initiatives to integrate greater amount of VRE in the power system to help achieve 2030 target of the Pan-Arab Renewable Energy Strategy – increases the reliability and flexibility of the system, and therefore smoothens the variability of renewable energy and eases its integration.

Other countries: In the same line as the GCC Interconnection system, there are other experiences around the world that have integrated two or more power systems in order to achieve the benefits from a single broader balancing area. Nord Pool is the world's first multinational exchange for trading electric power and is currently the largest electricity market in Europe (offering both day-ahead and intraday markets), which facilitates balancing the overall system within a wider area. Another remarkable experience due to its large share of renewable energy is the Grid Control Cooperation, which create a balancing area with the participation of TSOs from Belgium, Germany, the Netherlands, Denmark, Switzerland and Czech Republic. The idea of the Grid Control Cooperation is to control reserves the whole area like in a single fictitious control area that enables flexible response in case of imbalances or network bottlenecks. In Latin America, the initiative known as SINEA (Andean Electrical Interconnection) seeks to create an Andean power corridor by building infrastructure to connect the power grids of Colombia, Ecuador, Peru, Bolivia and Chile to achieve mutual support to overcome contingencies. The implementation of this concept smoothens variability and hence eases the penetration of VRE. Other regions can learn from these experiences in order to create broader balancing areas that fosters the integration of VRE.

Sources: GCCIA, 2013; Al-Ebrahim, 2014; Dobbeni, 2014

Box 15: Data ownership rights – California, US

Background: Guided by the remarkable growth in rooftop solar PV in California – in 2013 the total installations was doubled compared to the previous year, installing more rooftop solar in a single year than in the previous 30 years combined and reaching more than 2GW –, the California Public Utilities Commission (CPUC) signed on May 1, 2014 a decision to adopt rules to provide access to energy usage and usage-related data to local government entities, academia, researchers, and state and federal agencies while protecting the privacy of consumers' personal data. The aim of this decision is to guide California's development of a Smart Grid System and to facilitate access to energy data for Smart Grid stakeholders needing data to fulfill their statutory requirements. This decision considered 12 possible cases that constitutes specific requests for energy consumption data from stakeholders and the guideline to proceed each request.

Results: The decision taken by CPUC can be divided into six functions: (1) to direct energy and energy-related usage information that can be used to identify an individual, family or personal information about consumer habits – to the University of California or other educational institutions for research purposes; (2) to lead utilities to publish on a quarterly basis the total and average monthly usage of electricity and natural gas by zip code and by customer class (residential, commercial, industrial, agriculture); (3) to direct utilities to make available to local governments usage and usage-related data in a yearly, quarterly and monthly basis as long as the data request meets certain privacy protection measures; (4) to direct utilities to provide energy data to State and federal government entities that require data to fulfill their statutory obligations; (5) a formal process whereby stakeholders can request usage and usage-related data from utilities; (6) an Energy Data Access Committee to advise the utilities on process improvements and best practices related to data access, as well as help to mediate in the interaction between the utilities and data requesters, *e.g.* mediating disagreements between the two parts. Data is publically available from the websites of the utilities (see *e.g.*: https://pge-energydatarequest.com/).

Other countries: The rapid development and growing interest in smart grid technologies worldwide has raised a debate about data ownership and the protection of private information that can be obtained from the detailed data collected from consumers. This will be particularly relevant for countries with high shares of renewable power production by households and local communities. Currently, there is not global consensus of whether the data ownership resides with consumers because they generate the data, with utilities because they invest in the infrastructure to transmit and collect the data or a hybrid solution. Other countries can learn from the CPUC initiative to protect data while at the same time make an effective use of it by stating clear procedures and access rights over the data before the implementation of smart grid technologies. In contrast, in Boulder (Colorado, USA) in 2008 a fully-functioning smart city project powered by a self-monitoring smart grid was created without the prior settlement of rules defining data ownership and access rights. The lack of these rules triggered some disagreements regarding ownership, access and use of data for the different access to other entities that stakeholders, *i.e.* it was seen that data ownership may allow utilities to block could provide other benefits to consumers.

Sources: CPUC, 2014

curves, to augment balancing services and energy market prices.

According to models, the level of costs saving depends on how different the renewable energy sources in the cooperating regions are, and the level of cooperation in transmission developments across the border (Meeus and Saguan, 2011). Benefits have already been seen in developing wind power and pumped-storage hydro in combination in Europe, but competing concerns, such as the effect on electricity prices and environmental impacts, need to be taken into account (Gullberg, Ohlhorst, and Schreurs, 2014).

Data ownership rights

Lack of clarity regarding data privacy and ownership rights can potentially be a major barrier to acceptance and implementation of smart grid technologies (Fan, *et al.*, 2013) (NIST, 2014). Access to high resolution energy consumption data can provide insights to design measures such as direct load control or formulation of new tariff structures based on consumption patterns. However, they can also reveal a detailed picture of appliance use in a household. Potential opposition from consumers to provide access to data about energy consumption habits may make such measures difficult. In order to be able to make the best use of these technologies, these issues need to be clarified by defining data access, use and distribution rights, considering the data would be collected from the end user, the collection infrastructure may be installed by the distribution system operator or other actors in the energy supply chain, and it may be beneficial for other players (retailers, aggregators, energy service providers, etc., and eventually, for the consumers in the form of improved services) to access the data.

6.5 VRE grid integration measures for technology providers

Technology development in the power sector has been dominated by large multinational companies working close with utilities. The distributed nature of variable renewable power combined with the need for more localised control of power systems is changing this paradigm. With the influx of information and communication technology through smart grid technologies and the more pro-active role of consumers, new stakeholders like ICT and consumer service companies are entering the power sector. This means that new measures in terms data ownership and communication protocols will be required, independently from the share of variable renewable energy.

Communication standards

Communication standards for a smart grid infrastructure need to be defined at an early stage in its development. With technologies for smart grids being developed in different geographic regions and for applications in very different segments (grids, household appliances, buildings, etc.) by different stakeholders, measures need to be in place to ensure a set of common standards for communication between the different components of the smart grid (IEA, 2011)

There is considerable work already being done to establish common standards in different regions. In the US, standardisation efforts are being coordinated by the NIST. The NIST Framework and Roadmap for Smart Grid Interoperability Standards, already in its third version, identifies priority areas for standardisation and a list of standards to be developed and implemented (NIST, 2014). The IEEE works closely with the NIST and has created three task forces to focus on interoperability internationally in power engineering technology, information technology and communication technology (IEEE 2030-2011). In Europe, work is being done to establish common standards at the international level by the European Committee for Electrotechnical Standardisation (CENELEC) and the European Telecommunication Standards Union (ETSI) (CEN, CENELEC, ETSI, 2012). Similar initiatives are being taken forward in China, India, Japan (Fan, *et al.*, 2013) and South Korea.

Table 9: Relevance of VRE grid integration measures for regulators

Measure	Stakeholder engagement	Data needs	Flexibility conditions	Technology
Communication protocols	Regulators; Generators; Consumers; Energy service companies; ICT companies; Car companies	Power flow and demand data	Independent from VRE share; Competitive power markets, low generation flexibility	Smart meters; Smart inverters; Synchrophasors; Distributed battery and EV management; Virtual power plants; Direct load control

Box 16: Communication protocols – Japan

Background: From mid-2012 to mid-2014 more than 11 GW of renewables was installed in Japan and an additional 60 GW of renewable energy projects are in the pipeline, almost all are distributed PV plants (98%). However, some particular characteristics of Japan's power sector have hindered a greater deployment of renewable energy. For instance, Japan's transmission network is divided into two (50 Hz and 60 Hz), and its grid infrastructure is essentially broken up into ten separate grids operated by different utilities, which makes the cross-regional interconnection very weak. In this respect, smart grids can aid utilities in the integration of VRE into the grid. For Japan, the flexibility and deployment of smart grids can only be achieved with an appropriate degree of standardisation, thereby, standards are seen as a key element to achieve the required interoperability. For this reason the Ministry of Economy, Trade and Industry (METI) founded a strategy group with the aim of promoting Japan's contribution to international standardisation in the smart grids field.

Results: The fundamental role of standards in the development of Smart Grids (SG) lies in the fact that SG consists of many sub-systems that need common standards and interoperability. In January 2010 Japan released a road map on SG standardisation with the purpose of examining an international standardisation for smart grids in seven fields: wide area situational awareness (WASA) in transmission systems, demand side management (DSM), system-side energy storage, demand-side energy storage, electric vehicles (EV), advanced metering infrastructure (AMI) systems and distribution grid management. Each of these fields support the integration of VRE in the power system. In Japan, the Japan Smart Community Alliance (JSCA) promotes public-private cooperation and carries out various work and research for the development of roadmaps to promote international standardisation and strengthening collaboration. JSCA encompasses stakeholders (utilities, developers, manufacturers and institutions) from several sectors such as electric power, gas, automobile, ICT, construction, public sector and academia. The development and establishment of SG standards in Japan have allowed to develop R&D and pilot projects that are characterised by the high integration of VRE. For instance, there are four large scale SG pilot projects that started in 2010: Kyoto Keihanna District, Toyota City, Yokohama City and Kitakyushu City. Examples of SG technologies used for VRE integration are the coupling of rooftop solar PV systems with EVs, coupling solar PV to energy management systems, and the use of SG for dynamic pricing to support local consumption of VRE. Moreover, JSCA promotes SG projects in other countries, collaborating with standards organisations of different countries and establishing common international standards; this is the case with four smart community projects developed by Japan in association with China, India and the US (one in New Mexico and the other in Hawaii).

Other countries: As in Japan, different countries around the world have created institutions that support the establishment of standards for the development of smart grids. Some examples are NIST in the US, ETSI and CENELEC in Europe, SGCC in China, SCC in Canada and Standards Australia. Such national and regional standards bodies also allow effective participation in international standards bodies like the IEC (International Electrotechnical Commission) that develop international standards that cover all aspects of safety, interoperability and environmental impact; or GSGF (Global Smart Grid Federation) that bring together SG initiatives, ideas and standardisation from members around the world such as Australia, Canada, the EU, India, Israel, Japan, Korea, the US, among others.

Sources: METI, 2010; GSGF, 2014

However, because of smart grid development and deployment taking place at different time scales in different countries, there is a need to align standardisation initiatives in each of them to ensure interoperability among different components as well as regions, which can promote functionality as well as international competition.

7. RECOMMENDATIONS

This report shows that there is no single strategy that can be applied to the power sector transformation. Local conditions like the current generation mix, grid status, electricity demand profiles and growth, economic development, geographical and climatic conditions, and institutional structures like regulatory frameworks affect the sequence and combination of measures that will be relevant.

As a result, the framework for the development of a national roadmap for renewable energy grid integration consists of two interlinked part activities. The first part activity is that policy makers need to continuously assess, evaluate and improve the national conditions to support the power sector transformation. This includes:

- Develop capabilities to collect and process data, and support capacity and network planning;
- Assess existing flexibility options and constraints;
- Create technological capabilities to develop, absorb, and test new technologies and solutions.

Through these processes, the integration of VRE can be guided from an early stage without the need for explicit measures to address VRE integration. In particular, capabilities to plan the appropriate generation mix, site locations, and network support can relatively simple support the integration of VRE. At the same time, these processes will form the starting point for any additional measures that will be identified through the development process for a national roadmap.

The second activity within the framework consists of the development of the national roadmap, which includes stakeholder engagement and selection of relevant VRE grid integration measures. Again, the selection of VRE grid integration measures depends on local circumstances, but there are a number of guiding principles that can be derived from experiences so far that can direct policy makers in the development of a national roadmap for renewable energy grid integration.

The first guiding principle is that technological solutions are available to deal with the technical challenges of connecting VRE into existing and developing power systems. This report shows that technical measures like grid connection measures, grid connection policies, forecasting or reliability reporting are important measures that can be introduced at an early stage. Furthermore, these measures can provide valuable information that can be used to improve capacity and network planning at later stages.

The second guiding principle is that policy makers should consider the system-wide implications of increasing VRE at an early stage. VRE will change the business models of existing utilities, will push system operators beyond current practices, will allow new stakeholders to enter the power sector, and will encourage a more pro-active role of local distribution companies and electricity consumers. Consequently, policy makers should not only focus on VRE grid integration measures affecting the generation side, but also explore those that have a more system-wide impact.

The third guiding principle is that the integration of VRE is not a linear process, even though the share of VRE may grow linearly. In particular, VRE will often compete with flexible power plants at low shares, whilst they are complementary as the share VRE increases. The non-linearity can also be found in technology development, where technologies may become obsolete as they improve and costs reduce. From this perspective, measures that support flexibility within the system will remain more relevant as conditions change. Sub-hourly scheduling or power market designs, congestion management through nodal pricing, or market integration are examples of such measures.

The fourth guiding principle is that overarching policy frameworks need to ensure resource adequacy at all times, but that adequacy should be stimulated in all power sector assets, including demand side management, energy efficiency and international cooperation. Consequently, stranded assets of high-carbon generation capacity need to be avoided and deliberately removed as VRE resources are added to the system.

The fifth guiding principle is that new stakeholders are to be expected, and that many of institutional frameworks will need to be revisited. This includes existing structures governing the operations of energy planning institutions, utilities, regulators and finance institutions. In particular, the opportunities for distributed control through VRE coupled with smart grid technologies may create different paradigms for governing the power sector. Consequently, public engagement around the power sector transformation and measures such as attracting new investments, the engagement of consumers through new tariff structures, and models for self-consumption, might seem far away, but their potential impacts need to be evaluated at an early stage.

This report also shows that countries already have experience with the different VRE grid integration measures and their effects on the power system. Therefore, international cooperation will be an important instrument to facilitate and accelerate the deployment ofVRE. This includes fora where policy makers can share their experiences in establishing new measures to support the power sector transformation, but also platforms where regulators, system operators, utilities and technology developers can share their concerns and experiences among and with each other.

In the end, it is clear that power systems based on renewable energy can provide reliable, secure, affordable, and clean electricity to fuel the economy. The pathway to reach this objective requires substantial financial and political investments. In most cases, the governments will have to take lead regarding the political investments for this trajectory. The private sector will be needed for the financial investments. A national roadmap on the integration of VRE grid integration will be a crucial tool to ensure that interests remain aligned.

REFERENCES

AEE (Agentur für Erneuenbare Energien). (2013). *Definition unde Marketanalyse von Bürgerenergie in Deutschland (in German).* Bremen: AEE. *www.unendlich-viel-energie.de/media/file/198.trendresearch_Definition_und_Marktanalyse_von_Buergerenergie_in_Deutschland_okt13..pdf*

Agora Energiewende. (2015). *The European Power System in 2030: Flexibility Challenges and Integration Benefits.* Berlin: Agora Energiewende. *www.agora-energiewende.de/fileadmin/Projekte/2014/Ein-flexibler-Strommarkt-2030/Agora_European_Flexibility_Challenges_Integration_Benefits_WEB_Rev1.pdf*

Al-Ebrahim, A. (2014). Developing Power Trade through the GCC Interconnector. *3rd PowerTrade Forum.* Abu Dhabi: GCCIA. *www.gccia.com.sa/publications/2014/Session%203/Developing%20Power%20Trade%20through%20the%20GCC%20Interconnector%20-%20Ahmed%20Ali%20Al-Ebrahim%20(COO,%20GCCIA).pdf*

Ambrose, *H., et al*. (2014). Driving rural energy access: a second-life applicatino for electric-vehicle batteries. *Environmental research letters, 9*(9). *http://iopscience.iop.org/article/10.1088/1748-9326/9/9/094004;jsessionid=2865A783B8C00637FB9A0BBF9D1639AC.c1*

AEMO (Australian Energy Market Operator. (2014). *Australia Wind Energy Forecasting System.* Canberra: AEMO. *www.aemo.com.au/Electricity/Market-Operations/Dispatch/AWEFS*

BDEW (Bundesverband der Energie- und Wasserwirtschaft). (2013). *BDEW-Roadmap. Realistic Steps for the Implementation of Smart Grids in Germany.* Berlin: BDEW. *www.bdew.de/internet.nsf/id/E9DB33D6E6784CBBC1257BBB00363F7E/$file/BDEW_Roadm*

BMUB (Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit). (2015). *Projektionsbericht 2015 gemäss Verordnung 525/2013/EU (in german).* Berlin: Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit. *www.bmub.bund.de/fileadmin/Daten_BMU/Download_PDF/Klimaschutz/projektionsbericht_2015_zusammenfassung_bf.pdf*

BMWi (Bundesministerium für Wirtschaft und Energie). (2014). *Report of the Federal Government on Energy Research 2014.* Berlin: BMWi. *www.bmwi.de/BMWi/Redaktion/PDF/Publikationen/report-of-the-federal-government-on-energy-research-2014-englisch,property=pdf,bereich=bmwi2012,sprache=de,rwb=true.pdf*

BMWi. (2015). *An electricity market for Germany's energy transition.* Berlin: BMWi. *www.bmwi.de/EN/Service/publications,did=721538.html*

Boie, I., *et al*. (2014). Efficient strategies for the integration of reneawble energy into future energy infrastructures in Europe – An analysis based on transnational modeling and case studies for nine European regions. *Energy Policy, 67*, 170-185. *www.isi-cmspflege.de/isi-wAssets/docs/x/de/publikationen/Efficient-strategies-for-the-integration-of-RE-into-future-energy-infrastructures_Final-Paper_EP.pdf*

C21 (21st Century Power Partnership). (2015). *Status Report on Power System Transformation.* Boulder, CO: NREL. *www.nrel.gov/docs/fy15osti/63366.pdf*

CEM (Clean Energy Ministerial) . (2015). *Joint Statement of the CEM Power System Challenge.* Merida, Mexico: CEM. *www.cleanenergyministerial.org/portals/2/pdfs/CEM6-CEMPowerSystemChallenge-JointStatement.pdf*

CEN (European Committee for Standardisation), CENELEC (European Committee for Electrotechnical Standardisation), ETSI (European Telecommunications Standards Institute) (2012). *Smart Grid Coordination Group. Smart Grid Reference Architecture.* Brussels: CEN-CENELEC-ETSI. *http://ec.europa.eu/energy/sites/ener/files/documents/xpert_group1_reference_architecture.pdf*

CERCE (Centro de Controle de Energias Renovables (2010). *Centro de Controle de Energias Renovables (Cecre) – con loucion (in Spanish).* Madrid: CERCE. *www.ree.es/es/sala-de-prensa/infografias-y-mapas/centro-de-control-de-energias-renovables-cecre-conlocucion*

Clean Energy Council. (2015). *Clean Energy Australia Report 2014.* Sydney: CEC. *www.cleanenergycouncil.org.au/cleanenergyaustralia*

Clo, S., Cataldi, A., and Zoppoli, P. (2015). The merit-order effect in the Italian power market: The impact of solar and wind generation on national wholesale electricity prices. *Energy Policy, 77*, 79-88, www.sciencedirect.com/science/article/pii/S0301421514006661

Cochran, J., Katz, J., and Miller, M. (2015). *Methods for procuring power system flexibility.* Greening the Grid. www.nrel.gov/docs/fy15osti/63040.pdf

Connolly, D., *et al*. (2010). A review of computer tools for analysing the integration of reneawble energy into various energy systems. *Applied Energy, 87*(4), 1059-1082. www.sciencedirect.com/science/article/pii/S0306261909004188

CPUC (California Public Utilities Commission). (2014). *Decision Adopting Rules to Provide Access to Energy Usage and Usage-Related Data while Protecting Privacy of Personal Data (14-05-016).* San Francisco: CPUC. http://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M090/K845/90845985.PDF

Cramton, P., and Ockenfels, A. (2012). Economics and Design of Capacity Markets for the Power Sector. *Zeitschrift fuer Energiewirtschaft, 36*(2), 113-134. http://link.springer.com/article/10.1007%2Fs12398-012-0084-2#page-1

CREG (Comision de Regulacion de Energia y Gas). (2011). *Energia firme para el cargo por confiabilidad de plantas Eolicas.* Bogota: CREG. http://apolo.creg.gov.co/Publicac.nsf/1aed427ff782911965256751001e9e55/d5efa6c2d564b75b052578f0007b1108/$FILE/D-075-11%20ENERG%C3%8DA%20FIRME%20PARA%20EL%20CARGO%20POR%20CONFIABILIDAD%20DE%20PLANTAS%20E%C3%93LICAS.pdf

CREG. (2015, September 4). *What is Reliability Charge?* Reliability Charge. Regulatory Scheme to Guarantee the Reliability in the Supply of Electric Energy in Colombia. A Long Term Vision. Bogota: CREG.: www.creg.gov.co/cxc/english/que_es/que_es.htm

DEA (Danish Energy Agency). (2010). *Energy Policy Toolkit on System Integration of Wind Power. Experiences from Denmark.* Copenhagen: DEA. www.ens.dk/sites/ens.dk/files/climate-co2/low-carbon-transition-unit/danish-energy-policy-toolkit

DENA (Deutsche Energie Agentur). (2010). *dena Grid Study II: Integration of Renewable Energy Sources in the German Power Supply System from 2015 – 2020 with an Outlook to 2025.* Berlin: DENA.

Dobbeni, D. (2014). The Experiences in Europe, Asia and the Americas in Initiating Regional Power Market. *GCCIA 3rd Regional Power Trade Forum.* Abu Dhabi: GCCIA; GO15. www.gccia.com.sa/publications/2014/Session%201/Experiences%20in%20Europe,%20Asia%20and%20Americas%20-%20Daniel%20Dobbeni%20(Chairman,%20GO-15).pdf

Dondi, P., *et al*. (2003). Network integration of distributed power generation. *Journal of Power Sources, 106*(1-2), 1–9. www.ingentaconnect.com/content/els/03787753/2002/00000106/00000001/art01031

Dudurych, I. (2010). On-line assessment of secure level of wind on the Irish power system. *Power and Energy Society General Meeting* (pp. 1-29). Minneapolis: IEEE.

Dupont, B., *et al*. (2014). Demand response with locational dynamic pricing to support the integration of renewables. *Energy Policy, 67*, 344–354. www.sciencedirect.com/science/article/pii/S0301421513013220

EC (European Commission). (2015). *Addressing flexibity in enegy system models.* Petten: Joint Research Commission Science and Policy Reports. https://setis.ec.europa.eu/system/files/Addressing%20flexibility%20in%20energy%20system%20models.pdf

ECF (European Climate Foundation). (2012). *Power Perspectives 2030. On the road to a decarbonised power sector.* Brussels: ECF. www.roadmap2050.eu/attachments/files/PowerPerspectives2030_FullReport.pdf

Ecofys. (2015). *Power System Flexibility Strategic Roadmap.* Brussels: European Copper Institute. www.leonardo-energy.org/

ECRB (Energy Community Regulatory Board). (2013). *Analysis of existing grid connection rules and customer-friendliness.* ECRB. www.energy-community.org/portal/page/portal/ENC_HOME/DOCS/2010185/Grid_Connection_final_approved_23rd_ECRB.pdf

EEI (Edison Electric Institute). (2013). *Disruptive Challenges: Financial Implications and Strategic Responses to a Changing Retail Electric Business.* Washington D.C.: EEI. www.eei.org/ourissues/finance/documents/disruptivechallenges.pdf

Energinet. (2008). *Technical Regulation for Thermal Power Station Units of 1.5 MW and higher.* Fredericia, Denmark: Energinet. www.energinet.dk/SiteCollectionDocuments/Engelske%20dokumenter/El/Grid%20Code%203.2.3%20Power%20Unit%20above%201,5%20MW.pdf

Energinet. (2014). *Practitioner's guide to grid integration of variable renewable energy – electricity.* Copenhagen: Report for International Renewable Energy Agency.

EnerNex Corporation. (2011). *Eastern Wind Integration and Transmission Study.* Golden, CO: National Renewable Energy Laboratory. www.nrel.gov/docs/fy11osti/47078.pdf

ENTSO-E (European Network of Transmission System Operators for Electricity). (2013). *ENTSO-E Network Code for Requirements for Grid Connection Applicable to all Generators.* Brussels: ENTSO-E. http://networkcodes.entsoe.eu/wp-content/uploads/2013/08/130308_Final_Ve

EPRI (Electric Power Research Institute). (2014). *The Integrated Grid. Realizing the full value of central and distributed energy resources.* Palo Alto, CA: EPRI. http://integratedgrid.epri.com/

EWEA (European Wind Energy Association). (2015). *Offshore Wind Denmark.* Copenhagen: offshoreenergy.dk. http://www.offshoreenergy.dk/offshoreenergy/releases/on-off-magazines-1.aspx

EWI (Energiewirtschaftliches Institut), GWS(Gesellschaft für Wirtschaftliche Strukturforschung), Prognos. (2014). *Entwicklung der Energiemärkte – Energiereferenzprognose (in German).* Berlin: Studie im Auftrag des Bundesministeriums für Wirtschaft und Technologie. http://www.bmwi.de/BMWi/Redaktion/PDF/Publikationen/entwicklung-der-energiemaerkte-energiereferenzprognose-endbericht,property=pdf,bereich=bmwi2012,sprache=de,rwb=true.pdf

Fan, Z., *et al*. (2013). Smart Grid Communications: Overview of Research Challenges, Solutions, and Standardization Activities. *IEEE Communications Surveys Tutorials, 15*(1), 21-38. http://ieeexplore.ieee.org/xpl/login.jsp?tp=&arnumber=6129368&url=http%3A%2F%2Fieeexplore.ieee.org%2Fiel5%2F9739%2F5451756%2F06129368.pdf%3Farnumber%3D6129368

Favuzza, S., *et al*. (2015). Real-time pricing for aggregates energy resources in the Italian energy sector. *Energy, 87*, 251-258. www.sciencedirect.com/science/article/pii/S0360544215005939

Frankfurt School-UNEP (United Nations Environment Programme) Centre , BNEF (Bloomberg New Energy Finance). (2015). *Global Trends in Renewable Energy Investment 2015.* Frankfurt am Main: Franfurt School of Finance & Management. http://apps.unep.org/publications/pmtdocuments/-Global_trends_in_renewable_energy_investment_2015-201515028nefvisual8-mediumres.pdf.pdf

Fraunhofer ISE (Institute for Solar Energy Systems). (2015). Energy Charts. Gelsenkirchen. www.energy-charts.de/index.htm

Fulton, M. and Capalino, R. (2012). *The German Feed-in Tariff: Recent Policy Changes.* New York: Deutsche Bank Research. http://www.dbresearch.com/PROD/DBR_INTERNET_EN-PROD/PROD0000000000294376/The+German+Feed-in+Tariff:+Recent+Policy+Changes.pdf

GCCIA (Gulf Cooperation Council Interconnection Authority). (2013). *Annual Report 2012.* Dammam: GCCIA. http://www.gccia.com.sa/reports/2012%20Annual%20Report.pdf

GlobalData. (2015a). Power Generation database. Global Data. www.globaldata.com

GlobalData. (2015b). *High-voltage direct current converter stations, update 2015 – global market size, average pricing and equipment market share to 2020.* GlobalData.

Gordijn, J., and Akkermans, H. (2007). Business models for distributed generation in a liberalised market environment. *Electric Power Systems Research*, 1178-1188. http://citeseerx.ist.psu.edu/viewdoc/download;jsessionid=31579100645B9311C825611EB6B6ABD2?doi=10.1.1.461.648&rep=rep1&type=pdf

Gray, M., Leaton, J., Schuwerk, R., and Fulton, M. (2015). *Coal: Caught in the EU Utility Death Spiral.* London: Carbon Tracker Initiative. http://www.carbontracker.org/wp-content/uploads/2015/06/CTI-EU-Utilities-Report-v6-080615.pdf

GSGF (Global Smart Grids Forum). (2014). *GSGF Report. Smart Grid interoperability.* GSGF. www.smart-japan.org/english/vcms_lf/Resources/2014-07-Smart-Grid-Interoperability-Report.pdf

Gullberg, A., Ohlhorst, D., and Schreurs, M. (2014). Towards a low carbon energy future – Renewable energy cooperation between Germany and Norway. *Renewable Energy, 68*, 216-222. www.sciencedirect.com/science/article/pii/S096014811400072X

GWEC (Global Wind Energy Council). (2015). *Global Wind Statistics 2014.* Brussels: GWEC.

Hahn, T., *et al*. (2013). Model-based quantification of load shift potentials and optimized charging of electric vehicles. *Smart grid and renewable Energy, 4*, 398-408. *www.scirp.org/journal/PaperInformation.aspx?PaperID=35985*

Hammons, T. (2008). Integrating renewable energy sources into European grids. *International Journal of Electrical Power* and *Energy Systems, 30*(8), 462–475. *www.sciencedirect.com/science/article/pii/S0142061508000306*

Hasan, K., *et al*. (2013). Review of transmission schemes and case studies for renewable power integration into the remote grid. *Renewable and Sustainable Energy Reviews, 18*, 568-582. *www.sciencedirect.com/science/article/pii/S1364032112005965*

Hildmann, M., Ulbig, A., and Andersson, G. (2011). Electricity grid in-feed from renewable sources: A risk for pumped-storage hydro plants? *8th International Conference on the EuropeanEnergy Market (EEM)*, (pp. 185–190.). Zurich, Switzerland. *www.eeh.ee.ethz.ch/uploads/tx_ethpublications/EEM11_Hildmann_et_al.pdf*

Hirth, H., Ueckerdt, F., and Edenhofer, O. (2015). 2015. *Integration costs revisited – An economic framework for wind and solar variability, Renewable Energy, 17*, 925-939.

Hirth, L., and Ziegenhagen, I. (2013). Control Power and Variable Renewables: A Glimpse at German Data. *10th International Conference on the European Energy Market*, (pp. 1-10). Stockholm. *http://eeg.tuwien.ac.at/eeg.tuwien.ac.at_pages/events/AAEE-PhD-Day-2013/02_hirth.pdf*

Holttinen, H., *et al*. (2011). Impacts of Large Amounts of Wind Power on Design and Operation of Power Systems, Results of IEA Collaboration. *Wind Energy, 14*(2), 179-192. *http://onlinelibrary.wiley.com/doi/10.1002/we.410/abstract*

Holttinen, H., *et al*. (2009). *Design and Operation of Power Systems with Large Amounts of Wind Power.* Vuorimiehentie, Finland: Final Report IEA Wind Task 25 (2006-2008), VTT. *www.vtt.fi/inf/pdf/tiedotteet/2009/T2493.pdf*

IEA (International Energy Agency). (2011). *Harnessing Variable Renewables: A Guide to the Balancing Challenge.* Paris: IEA/OECD.

IEA. (2013). *Electricity Networks: Infrastructure and Operations.* Paris: IEA/OECD. *www.iea.org/publications/insights/insightpublications/ElectricityNetworks2013_FINAL.pdf*

IEA. (2014a). *Medium-Term Renewable Energy Market Report.* Paris: IEA/OECD. *www.iea.org/Textbase/npsum/MTrenew2014sum.pdf*

IEA. (2014b). *The Power of Transformation – Wind, Sun and the Economics of Flexible Power Systems.* Paris: IEA/OECD.

IEA. (2015). *How2Guide for Smart Grids in Distribution Networks. Roadmap Development and Implementation.* Paris: OECD/IEA. *www.iea.org/publications/freepublications/publication/TechnologyRoadmapHow2GuideforSmartGridsinDistributionNetworks.pdf*

IEA-ISGAN (International Smart Grid Action Network). (2012). *Smart Grid Contributions to Variable Renewable Resource Integration.* Boulder, CO.: IEA-ISGAN. *www.iea-isgan.org/index.php?r=home&c=5/378*

IEA-ISGAN. (2015). *The Role of smart Grids in Integrating Renewable Energy.* IEA-ISGAN. *www.nrel.gov/docs/fy15osti/63919.pdf*

IEA-RETD. (2014). *Residential Prosumers – Drivers and Policy Options.* Paris: IEA-RETD. *http://iea-retd.org/wp-content/uploads/2014/09/RE-PROSUMERS_IEA-RETD_2014.pdf*

IEA-RETD (Renewable Energy Technology Deployment). (2015). *Integration of Variable Renewables. Volume I: Main Report.* Paris: IEA-RETD;. *http://iea-retd.org/archives/publications/re-integration*

INSIGHT_E. (2014). *Curtailment: an option for cost-effective integration of variable renewable generation?* Brussels: INSIGHT_E. *www.insightenergy.org/ckeditor_assets/attachments/36/het2.pdf*

IRENA (International Renewable Energy Agency). (2012). *Electricity Storage and Renewables for Island Power. A Guide for Decision Makers.* Abu Dhabi: IRENA. *www.irena.org/publications*

IRENA. (2013). *Smart Grids and Renewables: A Guide for Effective Deployment.* Abu Dhabi: IRENA. *www.irena.org/publications*

IRENA. (2014a). *Rethinking Energy.* Abu Dhabi: IRENA. *www.irena.org/publications*

IRENA. (2014b). *REmap 2030: a renewable energy roadmap.* Abu Dhabi: IRENA. *www.irena.org/publications*

IRENA. (2014c). *Renewable Energy Technology Innovation Policy. A Process Development Guide.* Abu Dhabi: IRENA. www.irena.org/publications

IRENA. (2015a). *From Baseload to Peak: Renewables Provide a Reliable Solution.* Abu Dhabi: IRENA. www.irena.org/publications

IRENA. (2015b). *Renewable Energy Target Setting.* Abu Dhabi: IRENA. www.irena.org/publications

IRENA. (2015c). *Addressing Variable Renewables in Long-Term Energy Planning.* Abu Dhabi: IRENA.

IRENA. (2015d). *Renewable Power Generation Costs in 2014.* Abu Dhabi: IRENA. www.irena.org/publications

IRENA. (2015e). *Renewables and Electricity Storage. A technology roadmap for REmap 2030.* Abu Dhabi: IRENA. www.irena.org/publications

IRENA. (2015f). *Battery Storage for Renewables: Market Status and Technology Outlook.* Abu Dhabi: IRENA. www.irena.org/publications

IRENA. (2015g). *RD&D for Renewable Energy Technologies: Cooperation in Latin America and the Carribean.* Abu Dhabi: IRENA. www.irena.org/publications

IRENA. (2015h). *Africa Clean Energy Corridor: Analysis of infrastructure for Renewable Power in Eastern and Southern Africa.* Abu Dhabi: IRENA. www.irena.org/publications

IRENA. (2015i). *A Path to Prosperity: Renewable Energy for Islands. Second Edition.* Abu Dhabi: IRENA. www.irena.org/publications

IRENA. (2015j). *Grid Investments for Renewables.* Abu Dhabi: IRENA. www.irena.org/publications

IRENA. (2015k). *Smart Grids and Renewables: A Cost Benefit Analysis Guide for Developing Countries.* Abu Dhabi: IRENA. www.irena.org/publications

IRENA. (in press). *Study on Connection Grid Codes: Technical Regulations for Power Systems Enabling Higher Shares of Variable Renewable Energy* . Abu Dhabi: IRENA.

IRENA/IEA-ETSAP (Energy Technology Systems Analysis Program). (2013). *Thermal Energy Storage. Technology brief.* Abu Dhabi: IRENA;IEA-ETSAP. www.irena.org/DocumentDownloads/Publications/IRENA-ETSAP%20Tech%20Brief%20E17%20Thermal%20Energy%20Storage.pdf

IRENA/IEA-ETSAP. (2015). *Renewable Energy Integration in Power Grids.* Abu Dhabi: IRENA; IEA-ETSAP. www.irena.org/publications

Jones, L. (2012). *Strategies and Decision Support Systems for Integrating Variable Energy Resources in Control Centers for Reliable Grid Operations. Global Best Practices, Examples of Excellence and Lessons Learned.* Washington, D. C.: U.S. Department of Energy; Alstom. www.pfbach.dk/firma_pfb/doe_wind_integration_report_2012.pdf

Jones, L. (2014). *Renewable energy integration. Practical management of variability, uncertainty, and flexibility in power grids.* London; Waltham; San Diego.: Academic Press, Elsevier. http://store.elsevier.com/Renewable-Energy-Integration/Lawrence-Jones/isbn-9780124079106/

Kelly, G. (2011). *History and potential of renewable energy development in New Zealand.* Sydney: University of Wollongong. http://ro.uow.edu.au/cgi/viewcontent.cgi?article=1037&context=gsbpapers

KEPCO (Korean Electric Power Corporation). (2011). KEPCO's Demand-Side Management Programs. *Jeju Island, South Korea – How to develop DSM in Korea?* IEA Demand Side Management Energy Efficiency. www.ieadsm.org/wp/files/Exco%20File%20Library/Workshop%20-%20Jeju%20island,%20Korea%20-%20November%202011/4.%20Jeong-soo,%20You.pdf

Kröger-Vodde, A. (2009). *Report on the synthesis of results of previous work packages and derivation of best practice criteria to remove non-technological barriers of RES-E grid integration.* Promoting grid-related incentives for large-scale RES-E integration into the different European electricity systems. http://greennet.i-generation.at/files/D15_Report_SynthesisOfResults.pdf

Kwon, O.-S., Lim, J.-H., and Song, K.-B. (2014). An Analysis of Electric Demand Management Programs in Korea. *Journal of International Council on Electrical Engineering,* 3(4), 290-294. www.tandfonline.com/doi/pdf/10.5370/JICEE.2013.3.4.290

Lew, D., *et al.* (2010). *How Do High Levels of Wind and Solar Impact the Grid? The Western Wind and Solar Integration Study.* Boulder, CO: NREL. www.nrel.gov/docs/fy11osti/50057.pdf

Lew, D., *et al.* (2013). *Wind and Solar Curtailment.* Boulder, Co: NREL. www.nrel.gov/docs/fy13osti/60245.pdf

Mathiesen, V. (2011). *Mapping of selected markets with nodal pricing or similar systems. Australia, New Zealand and North American power markets.* Oslo: Norwegian Water Resources and Energy Directorate. www.nve.no/Global/Publikasjoner/Publikasjoner%202011/Report%202011/report2-11.pdf

Meeus, L., and Saguan, M. (2011). Innovating grid regulation to regulate grid innovation: From the Orkney Isles to Kriegers Flak via Italy. *Renewable Energy, 36*(6), 1761-1765. www.sciencedirect.com/science/article/pii/S0960148110005598

Mereghetti, M. (2014). *Italy to decide on renewable electricity imbalance charges in months.* ICIS. www.icis.com/resources/news/2014/04/11/9772038/italy-to-decide-on-renewable-electricity-imbalance-charges-in-months/

METI (Ministry of Economy, Trade and Industry). (2010). Smart Grid Standardization Activities in Japan. *1st Korea Smart Grid Week.* Tokyo: METI. www.ksgw.or.kr/down/pr/KSGW_HironoriNakanishi(101111).pdf

Milligan, M., *et al*. (2012). Markets to Facilitate Wind and Solar Energy Integration in the Bulk Power Supply: An IEA Task 25 Collaboration. *11th Annual International Workshop on Large-Scale Integration of Wind Power into Power Systems as Well as on Transmisison Networks for Offshore Wind Power Plants Conference.* Lisbon, Portugal. www.nrel.gov/docs/fy12osti/56212.pdf

Milligan, M., Kirby, B., and Beuning, S. (2010). Combing Balancing Area's Variability: Impacts on Wind Integration in the Western Interconnection. *WindPower 2010.* Dallas, TX: National Renewable Energy Centre Conference Paper. www.nrel.gov/docs/fy10osti/48249.pdf

MIT (Massachussettes Institute of Technology). (2011). *The Future of the Electric Grid: An Interdisciplinary MIT Study.* Cambridge, MA: MIT. http://web.mit.edu/mitei/research/studies/the-electric-grid-2011.shtml.

Morales, A., *et al*. (2008). Advanced grid requirements for the integration of wind farms into the Spanish transmission system. *IET Renewable Power Generation, 2*(1), 47-59.

Morales, J., *et al*. (2015). *Integrating Renewables in Electricity Markets. Operational Problems.* New York: Springer US. http://link.springer.com/book/10.1007/978-1-4614-9411-9

Navigant Consulting. (2012). *Potential role of Demand Response Resources in Maintaining Grid Stability and Integrating Variable Renewable Energy under California's 33 Percent Renewable Portfolio Standard.* San Francisco, CA: California's Demand Response Measurement and Evaulation Committee (DRMEC). www.calmac.org/publications/7-18-12_Final_White_Paper_on_Use_of_DR_for_Renewable_Energy_Integration.pdf

NERC (North American Electric Reliability Corporation). (2009). *Accommodating High Levels of Variable Generation.* Princeton, NJ: NERC. www.nerc.com/files/ivgtf_report_041609.pdf

NERC. (2015). *Glossary of Terms Used in NERC Reliability Standards.* Atlanta, GA; Washington D.C.: NERC. www.nerc.com/files/glossary_of_terms.pdf

NIST (National Institute of Standards and Technology). (2014). *NIST Framework and Roadmap for Smart Grid Interoperatbility Standards, Release 3.0.* Washington D.C.: NIST. www.nist.gov/smartgrid/upload/Draft-NIST-SG-Framework-3.pdf

NREL (National Renewable Energy Laboratory). (2012a). Lessons from large-Scale Renewable Energy Integration Studies. *2012 World Renewable Energy Forum, 13-17 May 2012.* Boulder, CO. www.nrel.gov/docs/fy12osti/54666.pdf

NREL. (2012b). *Renewable Electricity Futures Study.* Golden, CO: NREL. www.nrel.gov/analysis/re_futures/

NREL. (2014a). *Wind and Solar Energy Curtailment: Experience and Practices in the United States.* Boulder, CO: NREL. www.nrel.gov/docs/fy14osti/60983.pdf

NREL. (2014b). *Evolution of Wholesale Electricity Market Designing with Increasing Levels of Renewable Generation.* Boulder, CO; Lemont, IL;: NREL; Argonne National Laboratory. www.nrel.gov/docs/fy14osti/61765.pdf

Nykamp, S. (2013). *Integrating renewables in distribution grids: Storage, regulation and the interaction of different stakeholders in the future grids.* Twente: University of Twente. http://eprints.eemcs.utwente.nl/23851/

NZEM (New Zealand Electricity Market) Rules Committee. (2002). *Assessment of Outcomes Achieved by Full Nodal Pricing in the NZEM.* Trowbridge Deloitte. www.hks.harvard.edu/hepg/Papers/NZEM_nodal.pricing.assessment_12-18-02.pdf

Poncelet, K., *et al*. (2014). *The Importance of Integrating the Variability of Renewables in Long-term Energy Planning Models.* Leuven: TIME Working Paper – Energy and Environment. www.mech.kuleuven.be/en/tme/research/energy_environment/Pdf/wp-importance.pdf

Pudjianto, D., *et al*. (2013). *Grid Integration Cost of PhotoVoltaic Power Generation.* PV Parity;. *www.pvparity.eu/results/cost-and-benefits-of-pv-grid-integration/*

REserviceS. (2014). *Economic grid support services by wind and solar PV.* Brussels: EWEA. *www.reservices-project.eu/wp-content/uploads/REserviceS-full-publication-EN.pdf*

RMI (Rocky Mountain Institute), HOMER Energy. (2015). *The Economics of Load Defection.* Boulder, CO: RMI. *www.rmi.org/electricity_load_defection*

Schroeder, A., *et al*. (2013). The integration of renewable energies into the German transmission grid—A scenario comparison. *Energy Policy*, 61140–150.

Sensfuss, F., Ragwitz, M., and Genoese, M. (2007). *The Merit-order effect: A detailed analysis of the price effect of renewable electricity generation on spot market prices in Germany.* Karlsruhe: Fraunhofer Institute Systems and Innovation Research. *www.isi.fraunhofer.de/isi-wAssets/docs/e-x/working-papers-sustainability-and-innovation/merit-order-effect.pdf*

Shariatzadeh, F., Mandal, P., and Srivastava, A. (2015). Demand response for sustainable energy systems: A review, applicaiotn and implementation strategy. *Renewable and Sustainable Energy Reviews, 45*, 343-350. *www.sciencedirect.com/science/article/pii/S1364032115000726*

Sims, R., *et al*. (2011). Integration of Renewable Energy into Present and Future Energy systems. In O. Edenhofer, *et al.*, *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation* (pp. 609-690). Cambridge, UK; New York, US: Cambridge University Press.

Sourkounis, C., and Tourou, P. (2013). Grid Code Requirements for Wind Power Integration in Europe. *Conference Papers in Energy*, *2013.* Limassol, Cyprus. *www.hindawi.com/journals/cpis/2013/437674/*

Tarroja, B., *et al*. (2012). Metrics for evaluating the impacts of intermittent renewable generation on utility load-balancing. *Energy, 42*(1), 546–562. *www.sciencedirect.com/science/article/pii/S0360544212001351*

TEIAS (Turkish Electricity Transmission Company). (2012). Grid access and integration of renewable energy resources. *NARUC meeting.* NARUC. *www.naruc.org/international/documents/teias_presentation_eng.pdf*

The Brattle Group. (2015). *Integrating Renewable Energy into the Electricity Grid.* Boston, MA: AEE. *http://info.aee.net/hubfs/EPA/AEEI-Renewables-Grid-Integration-Case-Studies.pdf?t=1441315905264*

URA (Utilities Regulatory Authority). (2014). *Final Decision and Commission Order. In the matter of investigating and implementing feed-in tariffs and net-metering program for renewable energy in Port Vila.* Port Vila: Official Gazette, Republic of Vanuatu. *www.ura.gov.vu/attachments/article/100/U-0002-14%20Feed%20In%20Tariffs%20Final%20Decision%20-%20Office%20Gazette.pdf*

Weber, A., *et al*. (2013). *Long-term Power System Planning in the Context of Changing Policy Objectives – Conceptual Issues and Selected Evidence from Europe.* Berlin: Smart Energy for Europe Platform. *www.sefep.eu/activities/publications-1/SEFEP_grid%20planning_June2013.pdf*

Whited, M., Woolf, T., and Napolean, A. (2015). *Utility Performance Incentive Mechanisms.* Cambridge, MA: Synapse Energy Economics. *http://synapse-energy.com/sites/default/files/Utility%20Performance%20Incentive%20Mechanisms%2014-098_0.pdf*

World Bank. (2013). *Operating and Planning Electricity Grids with Variable Renewable Generation.* Washington DC: World Bank. *https://openknowledge.worldbank.org/bitstream/handle/10986/13103/757310PUB0EPI0001300pubdate02023013.pdf?sequence=1*

World Bank. (2015). *Bringing Variable Renewable Energy Up to Scale. Options for Grid Integration Using Natural Gas and Energy Storage.* Washington D.C.: World Bank. *https://openknowledge.worldbank.org/bitstream/handle/10986/21629/ESMAP_Bringing%20Variable%20Renewable%20Energy%20Up%20to%20Scale_VRE_TR006-15.pdf?sequence=4*

Zhang, S., and Li, X. (2012). Large scale wind power integration in China: Analysis from a policy perspective. *Renewable and Sustainable Energy Reviews, 16*(2), 1110–1115. *www.sciencedirect.com/science/article/pii/S1364032111005247*

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