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Power System Flexibility Strategic Roadmap

Preparing power systems to supply reliable power from variable energy resources

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Preparing power systems to supply reliable power from variable renewable energy sources

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Foreword

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Relying almost entirely on energy from variable renewable energy sources (vRES) will require a transformation in the way power systems are planned and operated. This report outlines steps for overcoming the challenges in creating power systems with the flexibility needed to maintain system security and reliability while relying primarily on variable energy resources. The work is largely a synthesis of the many reports and studies on this subject. It seeks to summarize that body of work for a less technical audience that will need to put in place the policies, technical changes, and institutional systems necessary to make the power system of the future a reality. For this work we gathered opinions from a dedicated power system flexibility advisory panel, through two meetings, e-mail exchanges, and an online survey.

The roadmap envisions a transformation performed over three phases or regimes:

- An initial phase with variable generation contributing up to about 10% of the energy demand, characterized by relatively mild changes to conventional power system operations and structures;
- A dynamic middle phase up to about 50% penetration by vRES characterized by phasing out conventional generation and a concerted effort to wring flexibility from existing infrastructure; and
- The high penetration phase that inevitably addresses how power systems operate over longer periods of weeks or months when variable generation will be in either short supply, or over-abundant supply.

Although the roadmap lays out a decades-long and incremental path, it presents actions that need to be taken in the immediate future. The needed policies, research, demonstration projects, and institutional changes need to start now precisely because the path is relatively long and the need so great.

The work presented in this report is organized in five chapters:

Chapter 1 (Introduction) describes the general debate related to the needed transformation of power systems in order to accommodate extra high levels of variable renewables and how this is directly related to increasing the power system flexibility. Further, we explain the notion of flexibility and discuss the status in today's systems.

Chapter 2 (Power System Flexibility Vision) analyses the seven key elements for the transition to reliable, low-cost power systems dependent primarily on vRES. In particular, we discuss the role of **demand,** the changes in **power markets**, the **control of variable renewable generators** for the provision of grid support services, the mechanisms needed to appropriately **reflect diversity-**

related benefits, the role of **bulk energy storage,** the **smart grid** evolution, and the management of **surplus energy events**.

Chapter 3 (Key Flexibility Challenges) discusses the key challenges for the transition to systems relying primarily to vRES. We present the three development regimes based on penetration levels of vRES and map the challenges on each regime.

Chapter 4 (Policy and Institutional Frameworks) dives deeper on the policy and institutional frameworks needed to address the challenges in each of the development regimes. For each regime we summarise the needed actions in comprehensive tables (**Flexibility Roadmap Policy Checklists**).

Chapter 5 (Roadmap summary) presents a roadmap that consists of the actions needed on the transition path towards ultra-high penetration levels of variable renewables.

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1 Introduction

1.1 The need for a Flexibility Roadmap

The need for reducing reliance on fossil resources is gaining currency around the world. Falling prices for renewable energy make the transition to societies based solely on renewable energy sources increasingly likely. Wind and solar energy are among the fastest growing sources of electric power generation today, and have already become competitive with conventional generation in some circumstances[1] as illustrated in Figure 1. Relying almost entirely on energy from vRES will require a transformation in the way power systems are planned and operated. The roadmap presented here explores how power systems driven primarily by renewable resources can work, and provides a path forward to facilitate the transition.

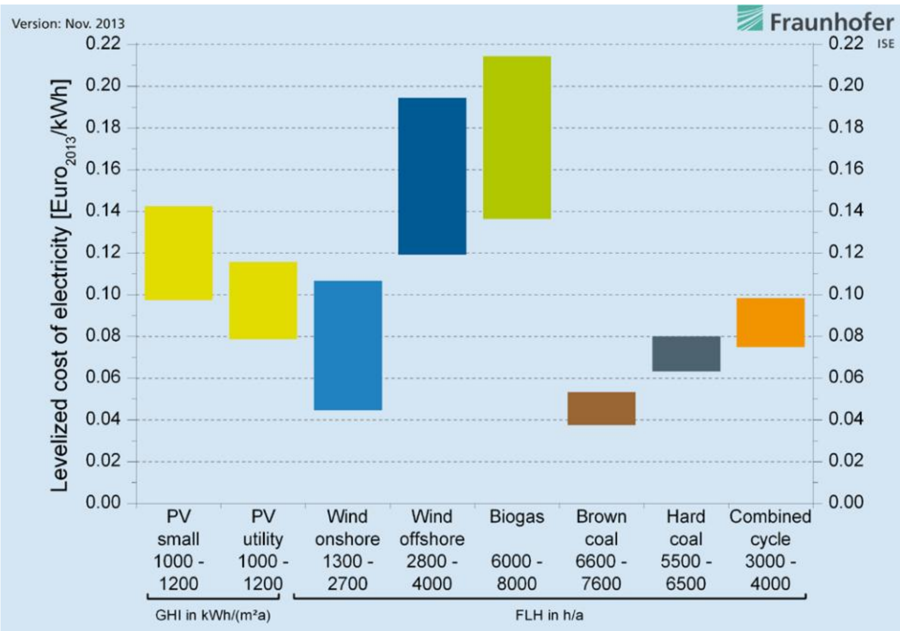


Figure 1 Cost of renewable resources becoming competitive with conventional power plants [1]

Power systems evolved over time based on utility companies responding to changing and somewhat unpredictable demand by controlling the output of a few relatively large utility-owned generators. The generators themselves also experienced unpredictable outages and routine regular maintenance, which also necessitated additional back-up power plants. Most conventional power generation today

[1] Unpacking the direct costs, subsidies, and externality costs of generation for comparison purposes is a complex task. See for example the recent report on subsidies and costs of EU energy [28] which points out the high costs of externalities of conventional generation. Despite the complexities, the point remains that wind and solar energy are already cost competitive with conventional resources in some areas today. Reference [7] has additional information about nearer term costs associated with high renewable energy scenarios.

is derived from fossil-fueled power plants that have been identified as major sources of carbon dioxide, a leading contributor to potentially devastating climate change. As a result, many regions are increasingly reliant on low-carbon solar and wind energy. Although originally touted for their environmental benefits, in recent years solar and wind power have become increasingly competitive (see Figure 1).

Wind and solar resources are also called variable renewable energy sources (vRES) because their electricity output is dependent on the availability of wind and sun, which vary somewhat unpredictably in time. Power systems relying on just a few percent of their energy from vRES can treat the resources largely the same way demand is treated—by adjusting the large controllable conventional generators to meet the net effect of demand minus the variable generation.

This approach has obvious limits. For example, if vRES are capable of supplying all the demand at a particular moment, all conventional resources may be turned off—there would be no conventional controllable power plants to adjust as needed when the demand or variable resource output changes. Broadly speaking, the ability to make adjustments necessary to balancing supply and demand and maintain system reliability is termed flexibility.

The importance of reducing power system carbon emissions, combined with the relative cost effectiveness of solar and wind resources calls to question whether a power system can provide the flexibility needed when vRES are the primary power source. This report identifies the sources of flexibility needed by a power system based on vRES, and outlines the needed steps to acquire them. The work is largely a synthesis of the many reports and studies on this subject, such as [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12]. It seeks to summarize that body of work for a less technical audience that will need to put in place the policies, technical changes, and institutional systems necessary to make the power system of the future a reality.

Power Systems

In broad terms, power systems consist of all the equipment and institutions that generate and deliver power to the end-use consumers. They are often divided into three interrelated parts:

- Generators that produce the power
- High voltage transmission system that transmits power from generators to distribution grids.
- Distribution grids that deliver power to end users

The separate parts often have separate, potentially multiple owners and operating entities. Transmission system operators are generally responsible for ensuring power system reliability and often host markets for wholesale power transactions that also serve the supply demand balancing function.

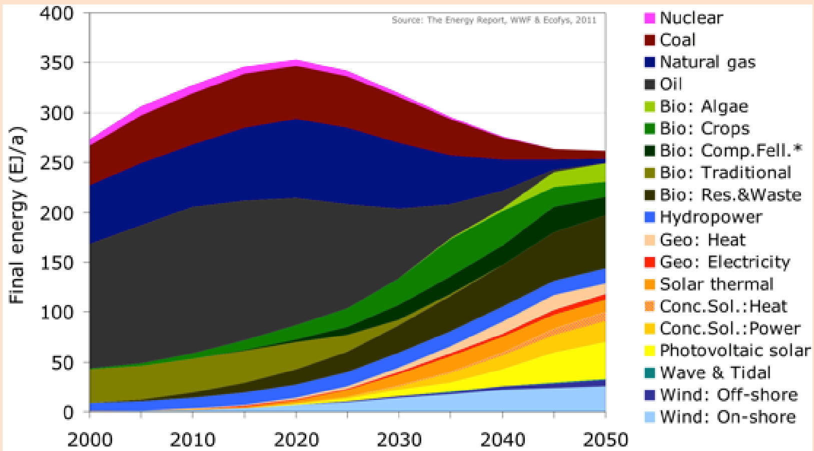
1.2 Power System Flexibility in a nutshell

Electric power production and consumption occur simultaneously. Mismatches between electric power production and demand risk wide-scale power system outages. Balancing supply and demand has historically been accomplished by adjusting the output of certain controllable power plants to maintain the system frequency in some predefined acceptable band. This practice largely continues today, except that the non-controllable output of wind and solar plants increases the need for flexibility in the power system to respond. These two key factors of variability and unpredictability shape the role of flexibility in power systems. [5]

Sufficiency of Renewable Resources

A key question is whether sufficient renewable energy potential exists to power consumer needs. Several studies have concluded that the earth's supply of renewable energy far exceeds human consumption of all sources of energy. For example, the solar energy striking the earth's surface in one and a half hours (480 EJ) is more than worldwide energy consumption from all sources combined in 2001 (430 EJ). Although less abundant than solar, analyses find that wind energy potential is many times current worldwide electric energy production.

Although wind and solar are the big two, other renewable resources such as hydropower, geothermal, biomass, and marine energy (wave and tidal) are already contributing to the world's energy production and can be added to the other resources. The figure below illustrates one view of how contributions from various non-fossil resources and energy efficiency could combine to meet the world's energy needs (not just electricity) by 2050.



World Energy Supply by Source, The Ecofys Energy Scenario, December 2010 [30]

Broadly speaking, flexibility is the ability of controllable power system components to produce or absorb power at different rates, over various timescales, and under various power system conditions. Keeping both key factors of variability and unpredictability in mind, reference [5] proposes a broad definition of flexibility as: *"flexibility expresses the extent to which a power system can modify electricity production or consumption in response to variability, expected or otherwise".* Controllable power plants used historically to address load variability have done double-duty to cover the additional variability from renewable resources. The stresses from this business-as-usual approach are already being felt as conventional generators become unable to provide the needed flexibility. Although it is tempting to think that the solution to this issue is energy storage, the tableau of solutions is much broader .

Power System Flexibility

Power systems are designed and operated to ensure that generation and demand are closely matched at all times. Power system flexibility refers to the ability to maintain that balance even during times when demand or supply change rapidly or widely.

Moving toward a low carbon economy implies a transformation in how power grids operate[2], with much greater emphasis on accommodating the unique characteristics of wind and solar power. It is perhaps not surprising that power systems of the last century optimized to use flexible generation to meet variable demand are not optimally designed in the case where both demand and supply are variable.

Despite the apparent challenges, sources of power system flexibility are available to accommodate very high levels of variable renewable generation at modest costs[3]. This report explores the flexibility options necessary to usher in the new low carbon energy world.

1.3 Flexibility Today – Making more efficient use of it

Given that the variability of added renewable resources can exceed the variability of demand, new strategies for accommodating those resources are needed. At these larger renewable penetration levels, several challenges become apparent, including: rapid changes in wind due to the passage of large-scale weather fronts that can outstrip controllable generators' ability to respond quickly enough; rapid changes of solar output in large penetration areas on partly cloudy days that could harm distribution system equipment; so-called "hot spots" of generation in geographic areas where available transmission might not be sufficient to move the power out; and generation of large amounts of power when demand is low, causing energy to be dumped as unusable. Additional flexibility is needed to address these challenges.

Power systems have traditionally been planned primarily to reliably meet peak demand for power, with flexibility being a secondary issue. As vRES become a larger part of power system resources, flexibility takes on a more central role. At very high penetration levels it may be necessary to add dedicated energy storage to power systems. However, the first and most economic steps involve maximizing the use of untapped existing flexibility and developing strategies for minimizing the level of needed flexibility. (see references [2], [3], [10]).

A wide range of actions can be taken in most power systems to better accommodate vRES. These actions fall into five categories:

Controllable Power Plants

Conventional power plants are grouped into three broad groups:

- Baseload power plants that tend to run as often as physcially possible, generally characterized by low fuel costs (e.g., coal and nuclear plants).
- Shoulder or mid-range plants that operate roughly between 25-75% of all hours (e.g., combined cycle gas plants).
- Peaking plants that tend to operate at less than about 25% of the time, often operating on just a few of the highest demand hours in the year.

Shoulder and peaking plants are designed to operate at different levels, depending on demand and are controlled through time to match varying demand. Note that hydro and other variable energy resources don't neatly fall entirely into a single group. For example, in some systems hydro fits all three groups.

[2] See references [2] and [10] for detailed descriptions of the components of the transformation.
[3] See for example, reference [7] for estimated incremental costs of low carbon scenarios for 2020 and 2030.

1. **Supply** options include making better use of conventional generation. In many systems only a fraction of available controllable resources are used to provide flexibility, or may be limited to providing flexibility in hourly increments. Changes in power system operating rules and markets may be needed to bring all available flexibility into play. Although vRES themselves are often treated as uncontrollable, sophisticated controls (e.g., limiting output under selected circumstances) can reduce the need for flexibility from other sources. In many systems, markets can be augmented to better recognize the value of flexibility and reflect that value to a wider range of conventional resources (e.g., sub-hourly dispatch of baseload and mid-load generators). The specific characteristics of vRES also affect the need for flexibility. Generally, wind and solar resources spread over larger geographic areas tend to result in less flexibility burden than the same resources co-located with one another. The reason for that is that fluctuations in output across more distantly located resources tend to cancel one another more than resources located close to one another. Few systems today offer any economic incentives relating to the inherent diversity of new vRES.
2. **Demand side flexibility options** include controlling demand, especially in applications that have a storage component. Opportunities for controlling demand exist in many energy-intensive industrial processes, irrigation and municipal water pumping, wastewater treatment, air and water heating and cooling (HVAC) systems, and electric vehicle charging. Energy efficiency can also be an important source of flexibility by freeing up generation resources to contribute flexibility as well as reshaping grid load profiles over time to better match available supply (e.g., solar output). Utilities have traditionally perceived end users as paying customers and not partners in supplying services to the grid, so new relationships must be formed to accomplish this change in a mutually satisfactory way. Demand-Side Management (DSM) is receiving increased focus as a potential source for low cost flexibility.
3. **Network:** Power system transmission and distribution networks allow the sharing of flexibility resources between and among different regions. Although large-scale investment in new transmission infrastructure is one avenue for enhancing flexibility, more flexibility can be obtained from the existing transmission system. For example, in many power grids the maximum allowed power transfer capability is computed based on assumed conditions, not real-time situational awareness, which allows real-time dynamic assessments of transmission capability, potentially increasing the ability to transfer power over the existing network. Other enhancements include dynamic voltage control needed to accommodate rapidly changing transmission loading, and power flow control technologies that allow grid operators the ability to better direct power flows over the network.
4. **Energy storage** can be seen as both generation and demand in the system. Most people associate energy storage with technologies that take energy from the grid in the form of electricity and return it as electricity, such as batteries and pumped hydro storage or compressed air energy storage (CAES) systems. In a broader sense, energy storage corresponds to a shifting of energy production and consumption in time allowing the bridging between periods of over- and under supply from vRES. In this respect further storage options such as hydrogen and other power-to-fuels show promise for longer term energy storage.

5. **System Operation and Markets** options include a number of important changes that may have significant potential to improve power grids' ability to accommodate vRES. These include automating market trading at the sub-hourly (e.g., 5-minute) level, opening markets for grid support services[4] to all resources and loads; so-called "capacity payments" to resources for their ability to provide needed grid support services; and other technical market issues such as "gate closure times" that can help access available flexibility, or reduce the need for it. One feature of large penetration renewable energy systems is occasional large supplies of renewable energy that drive wholesale electric market prices near, or below, zero. These events need to be reflected at the retail level so that markets can develop around making more efficient use of the sporadic availability of low or no cost electric energy (e.g., to displace fossil boilers).

Generally, accessing the untapped flexibility in today's grid can be a far lower cost means of accommodating vRES than new infrastructure investments. These adjustments could allow reaching significant vRES penetration levels; however represent significant changes in the way many of today's power systems are designed and operated.

1.4 Outlook of this report

The rest of this report is organized based on three key cornerstones of the **vision**, the **challenges** and the **actions**, towards 100% vRES power systems as follows:

Chapter 2 presents the **Power System Flexibility Vision** and analyses the seven key elements for the transition to reliable, low-cost power systems dependent primarily on vRES.

Chapter 3 **(Key Flexibility Challenges)** discusses the key challenges for the transition to systems relying primarily on vRES through a pathway of three key development regimes based on penetration levels.

Chapter 4 **(Policy and Institutional Frameworks)** dives deeper on the actions needed in terms of policy and institutional frameworks for address the challenges

Chapter 5 **(Roadmap summary)** presents a roadmap that consists of the actions needed on the transition path towards ultra-high penetration levels of variable renewables.

[4] The term "grid support services" here is adopted from *Economic grid support services by* [8]. It is broadly defined as services needed for voltage and frequency support, and system restoration. Some or all of these services are also known as ancillary services in some markets, without consistent usage.

2 Power System Flexibility Vision

2.1 Vision Elements

Ultimately, the transition to reliable, low-cost power systems dependent primarily on variable renewable energy sources (vRES) involves a transformation in how power systems are planned and operated. How that transformation unfolds will depend on the conditions of the specific power system—the available renewable resources, availability of energy storage opportunities, composition of demand, interconnectedness to other power grids, etc. Nevertheless, there are certain elements that are likely common to all, which are illustrated in the Figure below.

Figure 2 Key elements of the flexibility vision

In a nutshell, the key characteristics of these elements are:

1. Flexibility and energy storage inherent in **demand** will be more fully exploited, with today's power consumers becoming power system partners.
2. Wholesale and ancillary services **power markets** will become more liquid, operating closer to real-time and their geographic reach will be expanded in order to access existing sources of flexibility and exploit the diversity of distant vRES.
3. **Variable renewable generators will be controlled** to provide grid support services and to reduce variability and uncertainty deriving from uncontrolled renewable resources.
4. Price incentives or other mechanisms will be instituted that appropriately **reflect diversity-related benefits** in the development of new vRES.

5. **Bulk energy storage** will be instituted to cover longer periods (weeks to months) of low renewable energy supply.[5]
6. More sophisticated communication and controls will be instituted to coordinate flexible resources across supply and demand, and across transmission and distribution grids—the "**smart grid**."
7. New electric energy uses will arise to capitalize on the occasional, but increasingly frequent **surplus energy events**.

The relative importance of these features will vary from system to system depending on local conditions, but each of them represents an important contribution to developing systems capable of functioning efficiently and reliably relying on vRES.

It is important to recognize the role these features play and begin focusing on them even at relatively modest levels of vRES penetration levels because they cannot be instituted overnight. The history of renewable resource development has generally been somewhat near-sighted, focusing on establishing markets, technologies, and incentives to maximize energy production. The strategy of implementing production-based incentives has largely succeeded in encouraging the development of renewable resources. However, different strategies need to be pursued if the end goal is to reach higher vRES shares.

Reaching higher penetration levels requires creating a solid foundation in the early stages of resource development. Unlike the traditional evolution of grids, the concept of an evolving "integrated grid" arises, where the traditional boundaries between generation, transmission and distribution are disappearing in a fast pace. This vision is intended to present an outline of the foundations of this transition, explaining the role and importance of each of its components.

2.2 Vision Details

2.2.1 Exploiting Demand Side Flexibility[6]

Conventional power systems primarily rely on controlling supply to adjust power generation levels up or down to match changes in demand. Some systems have instituted demand management programs that remunerate certain power consumers for reducing demand on request, generally for a limited number of hours each year when weather extremes result in the highest levels of demand. Participating power consumers have the ability to alter the timing of their consumption without unduly affecting their business or costs. Examples include short-duration (e.g., 30 minute) cycling of air conditioning units and irrigators reducing pumping loads during heavy demand periods. Demand management programs have traditionally been instituted because the alternative of building additional power generators to accommodate the few hours of highest annual demand is more costly.

As power systems transition away from more controllable generating technologies to rely primarily on vRES, advanced demand management becomes a vital source of power system flexibility. Advanced

[5] This longer-term energy storage is termed bulk energy storage here to distinguish energy storage providing shorter-term system flexibility needs.

[6] Reference [3] contains a detailed description of demand's important role in providing power system flexibility.

demand management is more than just reducing demand where that is possible. Advanced demand management programs:

- Exploit potential flexibility in a broad array of end uses to both increase and decrease demand.
- Exercise available flexibility on a regular basis as appropriate[7].
- Expand demand flexibility by adding storage capability where warranted.
- Coordinate dynamic demand management with energy efficiency opportunities.

Many power end uses involve an energy storage component. For example, municipal water and irrigation pumping may involve physical reservoir space that allows some flexibility in the timing of the pumping. Heating and cooling applications naturally involve energy storage in the form of thermal mass. In some cases, it may be cost effective to enhance the flexibility of such end uses by adding to the existing storage capability. For example, buildings may add insulated water tanks to store heated or cooled water that would allow the heating and cooling systems more optionality in when they operate.

Additionally, implementing new demand technologies may represent another significant source of power system flexibility, specifically through the increased electrification of the transport and heating sectors. For example, vehicles powered directly or indirectly by electricity could add a distributed energy storage capacity close to demand. Another example may be new high-efficiency heat pump technology displacing fossil heating applications and introducing an additional source of flexibility, especially when combined with thermal storage (e.g. hot water).

2.2.2 Expanded and Liberalized Markets

Markets look significantly different in power systems relying primarily on zero variable cost resources. The value of energy at the wholesale level becomes very low due to the abundance of zero variable cost energy. Grid support services likely come to dominate market trading, reflecting the increased value of flexibility and optionality necessary to ensure reliable power from vRES. Alternatively, markets could shift to long-term products, e.g. capacity markets for controllable generation and some continued support for vRES. In any case there are some common market characteristics expected from this transition, discussed below.

Ensuring low cost service will require markets open to as many participants as possible. Markets will extend to non-traditional participants, potentially including players at the retail level. Participants will include traditional generating resources, vRES, distribution system-level generation, demand resources, and energy storage.

The markets will transact in near real time in time increments not greater than ten minutes long, in order to reduce the need for flexibility due to vRES. Reducing gate closure times will translate into increasing forecast accuracy, while increasing the operational granularity will allow the system to more efficiently adapt to the changes in the power output from vRES.

[7] Most conventional demand management programs rely on requesting alterations in demand over a very few hours each year. Advanced demand management will tap demand flexibility that can be activated many times a day, or hour.

Markets will cross regional and national borders to the extent possible, both to allow participation from a broader range of potential sources of flexibility, but also to average variability over more diverse vRES. Just as the energy use in a single household represents far greater variability and far lower predictability than a community of households, similar diversity benefits accrue to aggregating the output of geographically distant vRES. Accommodating the variability of resources in small balkanized power markets is a far greater task than accommodating the variability of the combined resources.

Reaching across today's boundaries will require institutional adjustments and coalescing artificially separated power systems. Additional transmission construction can also increase the interconnectedness of disparate markets and needs to be considered.

2.2.3 Grid Support Services from Renewable Energy[8]

Incentives designed to encourage renewable energy production tacitly assume that conventional generation continues to supply needed grid support services such as frequency control, contingency reserves, voltage control, and balancing services. As systems rely more heavily on vRES, those grid services will need to come from the renewable resources themselves—generally incurring a trade-off between the energy produced and the services provided. Effecting this change will require changes in both markets and technology.

Market mechanisms that provide renewable resources incentives to prioritize maximizing output over all other services will need to evolve; in particular to lessen penalties for reduced generation and to increase incentives for providing grid support services. In most power systems today, the availability of grid support services from conventional generation, combined with the inherent market disincentives and often the direct exclusion of non-conventional units for providing system services effectively preclude variable renewable generators from providing the services that will ultimately be needed from them [13]. In regions where variable generation is providing a significant share of total electricity demand incentive structures should change or they risk incurring much higher retrofit costs later as penetration levels rise.

Although there is some evidence that systems powered exclusively by renewable resources can work [14], there is little experience with such systems, and much uncertainty about exactly how the systems need to be designed. Additional research is needed, and new standards put in place to ensure that the needed functionality exists. Power systems relying primarily on vRES will depend on those resources providing a significant amount of the flexibility now coming from conventional resources.

2.2.4 Encouraging Renewable Resource Diversity[9]

The primary consideration for siting and building new renewable resources has been the cost per unit of energy generated without regard to the quality or relative timing of the resource with respect to other variable generating resources. Wind resources in particular have tended to be developed where

[8] Refer to [8] and [2] for in depth review of vRES providing grid support services.

[9] See references [3] and [4] for in-depth coverage of the benefits of geographic diversity and the means of achieving it.

the combination of wind resource and transmission access are relatively abundant. As a consequence, resources tend to be clumped together and the output of the variable generation has a tendency to rise and fall together. This behavior increases the flexibility burden on the power system compared to resources that do not act together in that way.

Some regions have adopted renewable energy development zones to provide incentives to spread resource development among different weather regimes that may be less strongly correlated with one another. Another possibility is to specifically recognize the extent to which new resources are correlated with existing resources, providing economic incentives to locate in areas that are less strongly correlated with the output of existing resources. The advantages of accessing diversity need to be balanced against the cost of new transmission infrastructure. Accurate valuation of diversity along with well-planned development zones can ensure the most cost-effective and least disruptive transmission construction.

A good example of the potential importance of this type of planning is exhibited in the US state of California where wind resources tend to be stronger at night and solar output peaks occur during the day. There is an advantageous combination of solar and wind that has the potential to strongly affect the cost of accommodating a system composed nearly entirely of variable renewable generation.

2.2.5 Role of Bulk Energy Storage

Electric power is generated and consumed simultaneously. Today, balancing supply and demand is accomplished largely by adjusting the supply of power from controllable generators to match demand for power. Energy is typically removed in the form of water stored in hydro reservoirs, natural gas in gas storage fields and pipelines, and coal piles as needed to accommodate the varying demand for power. These fuel sources provide a form of energy storage that power systems rely on to maintain reliable supplies of power under varying conditions.

As vRES become the primary source of energy, the ability to maintain supply and demand balance by controlling conventional power plants is vastly diminished. Something else needs to happen. As described above, some of this can be supplied by adjusting flexible demand, and some from controlling the output of the renewable resources themselves. However, there is a limit to which these strategies can fill the need. This is primarily because wind and solar resources can be in very limited supply for periods of weeks or even months at a time. The need for longer-term energy storage is termed bulk energy storage here to distinguish energy storage providing shorter-term system flexibility needs.

Today, conventional electric storage technologies such as pumped hydro, compressed air, and batteries are not generally capable of providing bulk energy storage sufficient to the need at high renewable resource penetration levels, either because of costs or lack of physical space to site the installations. During the transition to higher penetration levels, energy storage can be provided from demand by the increased coupling of the electricity sector to other sectors (such as heat, transport, industrial, etc). For example, by electrification of the heat sector, thermal storage extends to building stock equipped with heat pumps.

Energy storage becomes a vitally important source of flexibility when vRES reach the highest penetration levels. Although the energy storage technologies we depend on today are not likely the solutions of the future, there appear to be such solutions. Today, conventional resources take over for renewable resources when needed. One way that the future needs could be met is by those very same conventional resources burning synthesized carbon-neutral fuels.

Bio-based fuels are one possibility. Another possibility is fuel synthesized from electric power such as hydrogen or methane. Producing methane is an especially tantalizing possibility because methane is the primary constituent of natural gas. Methane could be stored in existing natural gas storage infrastructure and burned in existing natural gas power plants. Although this may not turn out to be the most economical solution, it is a feasible solution with today's technology. A German utility-scale (6 MW) methane synthesis plant began operation in 2013 [15]. It also opens the door to wider use of renewable-sourced electricity to provide transportation fuels— the original purpose of the German methane plant. By the time bulk energy storage is needed, there may be other solutions than synthesizing fuels. Energy storage technologies covering a near dizzying range of technology types are being pursued today. Battery technology is under very rapid development for use in the burgeoning electric vehicles market.

2.2.6 The Smart Grid

Conventional power systems are largely operated by controlling a relatively small number of large grid components such as generators and control devices (switches, transformer taps, reactors, etc.). Relying on a web of smaller, interconnected components such as distributed generators, distributed storage and power consuming devices introduces an order of magnitude increase in the complexity of power system operations, much of which will need to be automated and enabled with two-way communication. Power systems capable of coordinating and optimizing the burgeoning number of controllable devices is referred to as the "Smart Grid". Key elements of these systems are presented below.

The challenge of system operation

The complexity of operating systems with many more control points all along the path between generator and end user is a major undertaking of the Smart Grid. That complexity may be illustrated by a simple example. Consider the operation of a fully integrated electric storage water heater. On most hours, today's water heaters energize randomly

Smart Grid

According to [36], the concept of Smart Grid concerns an electricity network that can intelligently integrate the actions of all users connected to it - generators, consumers and those that do both - in order to efficiently deliver sustainable, economic and secure electricity supplies. A smart grid employs innovative products and services together with intelligent monitoring, control, communication, and self-healing technologies in order to:

- Better facilitate the connection and operation of generators of all sizes and technologies;
- Allow consumers to play a part in optimising the operation of the system;
- Reduce the environmental impact of the whole electricity supply system;
- Maintain or even improve the existing levels of system reliability, quality and security of supply;
- Maintain and improve the existing services;
- Foster market integration.

The driving forces behind smart grid today are efficiency and cost. However, the smart grid is a necessity for operating a grid primarily dependent on vRES.

around a set point temperature and after significant draws of hot water. The presence of a reservoir of water means that over most hours, the water heater can be energized or de-energized without adversely affecting the consumer's experience. Such a water heater can be operated or optimized around a range of potentially competing values:

- Availability of hot water to the consumer.
- Provision of transmission grid support services (e.g., reserves, balancing services, bulk storage).
- Alleviating transmission congestion.
- Power system peaking capability (traditional demand response).
- Distribution grid support services (e.g., voltage control).
- Distribution grid congestion response.

The wide array of potential services that makes controlling these devices attractive also adds to the complexity of doing so. Optimizing the use of the devices requires two-way communication in order to remotely sense the state of the device (e.g., the amount of hot water, current and historical demand), send control signals and to verify its response. Adding to the complication is that these services may be variously provided to and valued by the end user, the local distribution system operator, and the transmission grid operator. The optimization of a system of such devices means processing and optimizing over literally millions of such devices, which would also include a myriad of individual wind turbines, solar panels, and more advanced transmission system controls. Systems of the needed level of complexity are currently under development, but more research and demonstration are required.

Distribution systems: from passive to active microgrids

The introduction of distributed energy resources (DER)[10] in distribution networks creates a paradigm shift in power systems. In 'traditional' power systems, power generation is mainly connected to the high voltage transmission grid in the form of centrally controlled large scale power plants. Distribution grids were traditionally designed as 'passive' networks, containing mainly loads. In such power systems, power flows in one direction, from the high voltage transmission grid to the loads in the lower voltage levels of the system. Increased penetration levels of DER transform distribution grids to 'active' systems which, together with loads, contain high shares of generators and energy storage devices. This new system structure implies bi-directional power flows between distribution and transmission systems, since distribution grids will export power at times when local generation exceeds consumption. This evolution brings higher complexity in the management of distribution systems, but also new possibilities to optimise the overall system by allowing distribution systems to participate actively in the system operation and by allowing DER to participate actively in the distribution system management. [16], [9].

Such active distribution grids (or parts of distribution grids) can evolve to Microgrids, which are localized grids that can disconnect from the traditional grid to operate autonomously. Such network

[10] Distributed Energy Resources (DER) consist of small- to medium- scale resources connected to the lower voltage levels (distribution grids) of the system or near the end users. They include distributed generation (dispatchable or variable renewable based), small-scale energy storage, demand response, and new load from electrification of other sectors, such as transportation and industrial process heat.

elements and help mitigate grid disturbances to strengthen grid resilience, can play an important role in transforming the electric grid. Microgrids can strengthen grid resilience and help mitigate grid disturbances because they are able to continue operating while the main grid is down, and they can function as a grid resource for faster system response and recovery. [17]

Smart Transmission Systems

Transmission network expansion aids system flexibility by bringing additional resources to help meet system security needs. It is recognized that a significant expansion of transmission may be needed to reach the geographic availability of vRES, which is often met with public opposition. However, the need for expanding transmission can be ameliorated somewhat by leveraging the full potential of the exiting infrastructure. New technologies are expected to offer alternative solutions in two key areas—power flow control and dynamic assessment of transmission capability:

1. Power flow control: The flow of power over transmission systems is relatively uncontrolled in most power systems today. Power flows over transmission networks very similarly to the way water flows through pipes. Unlike water systems, there are few controls on flow rates or directionality of the flow of power over the grid. As a result, portions of the transmission system can become overloaded at the same time that other parts are underutilized. The introduction of special devices such as phase-shifters, direct current interconnects (HVDC lines) and other power electronic devices (FACTS) allow control of the volume of power flows over lines in much the same way as valves control flows in pipelines. Upgrading transmission system control and measurement technology needs to progress at least apace with efforts to expand the transmission line capacity so as to minimize the need for the social displacements and costs of new transmission lines.

2. Dynamic assessment of transmission capability: Transmission networks were planned and operated on the basis of relatively sparse controls and measurements. A key feature in using existing infrastructure more efficiently is to enable the dynamic assessment of the transmission status and capability. Collecting and organizing transmission system data many times a second, close to real-time, is a means of tapping more of the capacity of the power system as a whole. Dynamic Line Rating (DLR) technology is a key enabling factor, allowing transmission owners to determine capacity and apply line ratings in real time. Traditionally, transmission operators rely on static ratings for the capacity of transmission lines, which are normally conservatively determined based on "worst-case scenario" conditions. Demonstration projects presented in [18], confirmed the presence of real-time capacity above the static rating, in most instances, with up to 25% additional usable capacity made available for system operations.

The challenge of non-synchronous operation

One of the on-going concerns is operating power systems without a large fraction of synchronous generation. Most conventional power plants use synchronous generators, which involve an electro-mechanical coupling between the power grid and the spinning turbines. Wind and solar power plants typically inject power into the grid through power inverters that have significantly different properties than synchronous generators.

A largely untapped advantage of the non-synchronous power inverters is their potential controllability. For example, inverters can be designed and instructed to provide the inertia properties of synchronous generators. The controllability of these devices adds to the complexity of the control and communication problem in operating the smart grid of the future.

2.2.7 Efficient Use of Surplus Generation

The aforementioned measures will supply the needed power system flexibility to accommodate the variability of wind and solar resources, and maintain today's level of system reliability and power quality. However, ensuring an adequate supply under low resource availability conditions (e.g., calm winds in low-solar winter months) implies an over-abundance of energy during much of the rest of the time.

There are already periods on systems with significant penetrations of wind energy when wholesale market prices drop to zero, or even become negative[11]. As more vRES are added, these events will become more frequent and involve more energy. The two most challenging features of large-penetration variable renewable resource systems will be times of prolonged low productivity and times of over-abundance. Although much attention has been paid to the former because of traditional concerns of supply adequacy, it is likely that overabundance will be an equally important feature to manage.

While both wind and solar resources can turn down the power at will, making efficient use of the abundance variable generation will reduce the cost of the system of the future and help spread the use of carbon free renewable electricity into other economic sectors. It will be important to facilitate the development of markets around using this energy. A simple example is displacement of fossil boilers with electric boilers— electric boilers are relatively inexpensive devices that could be used intermittently to economic benefit in at least some applications.

It is likely that the full spectrum of cross-sectoral potential uses for inconsistent availability of abundant, low cost electric power has not been identified, and awaits a combination of more frequent occurrences and the development of retail markets to take advantage of these surpluses.

2.3 Flexibility vision: key takeaways

There are seven key characteristics that are likely common for the transition of power systems to a 100% reliance of vRES. Depending on the specifics of each system, the relative importance of these features will vary but in a nutshell what needs to be done is:

- **Demand** has to take an active role on the system management.
- **Power markets** should be expanded to new participants and shift towards real-time.
- **Renewable generators** should assume more responsibility contributing to system operation and security.
- **vRES resource diversity** should become a distinct consideration in the exploitation of new resources.

[11] Negative prices occur when generators are willing to pay "buyers" to take power. This can happen for a variety of reasons that include: contractual penalties for under-generating available renewable resource; base load resources that incur shut-down and start-up costs; or renewable resources receiving production-based subsidies.

- **Bulk energy storage** will be needed to enable seasonal balancing for allowing renewable energy to replace fossil fuels.
- Power networks should be transformed to **Smart Grids** to enable harnessing the full infrastructure potential.
- New uses of electricity should be promoted to allow the efficient use of **surplus generation**.

All these elements imply significant changes to the way the system was traditionally developed and operated and translate into specific technical and institutional challenges. These challenges are presented in the next chapter.

3 Key Flexibility Challenges

The biggest challenges with operating systems at the highest penetration levels relate to coping with the variability of these resources and to achieving the system transformation necessary for the widespread reliance on distributed energy resources (DER). Depending primarily on wind and solar resources poses significant challenges relating to bridging long periods of low renewable generation, and managing large surpluses of power during high availability periods. Coping with the flexibility needs in the emerging grid will entail the large-scale adoption of distributed resources. There are important challenges related to developing the needed communication and controls of a system relying on potentially millions of non-synchronous devices spread across both the transmission and distribution grids. Relying on distributed variable generation is an additional, but not wholly separate challenge. These challenges are addressed in more detail below.

3.1 Integrating Low Levels of Variable Resources (Near-term regime)

Relatively low levels of variable renewable generation can generally be integrated using existing infrastructure and operating procedures that are already in place to accommodate the variability and uncertainty of the pre-existing system. However, there are a number of challenges that emerge even in such regimes, signaling issues that become more evident at higher penetration levels.

The biggest cost is usually found to be the cost of holding reserves sufficient to cover lower than expected generation during the operating period (depending on the system, operating periods range from 15 minutes to 1 hour).[12] The biggest challenge here is ensuring the best possible forecast for each operating period, which in turn usually means allowing the renewable generation to be nominated as close to the beginning of the operating period as possible. This is due to the fact that shorter-range forecasts of variable renewable generation (e.g. 20 minutes before each operating hour) are more accurate than longer-range forecasts (e.g. 2-hours prior the operating hour), especially for wind generation. The difference can result in far lower reserve requirements, and similarly lower system-operating costs.

Another challenge comes in systems where significant amounts of variable generation consist of small to medium scale units interconnected to distribution systems. Variable generation radically changes the power profile of distribution grids, which at times may export power to the transmission system (bi-directional flows). This can necessitate substantial changes to distribution systems that originally designed to act primarily as passive networks hosting mainly loads. Such changes can include technical design aspects (e.g. protection coordination) and more fundamental aspects (e.g. more

[12] The costs of reserves refer in general to capital costs of backup units and to operational costs of generators that need to be available to respond to short-term unexpected changes in balancing needs. Incorporation of vRES leads to higher reserve needs due to reduced predictability and increased variability of supply. In low penetration levels, the additional reserves can be small compared to those already needed to accommodate the predictability and variability of demand.

active participation to the system operation and enhancement of the responsibilities to distribution system operators).

Geographic differences in resource availability result in distribution systems bearing uneven burdens in coping with variable generation. Usually the best resources are tapped first, leading to some local systems experiencing very high penetration levels even at low system-wide penetration regimes. These distribution systems are in a way the forerunners of integration challenges[13].

Grid Codes

Devices connecting to electric grids are normally subject to operating characteristics required by the grid operator. These technical requirements are called grid codes and include safety protocols and responses to power system events such as frequency or voltages deviations and outages.

Solar and wind grid codes have evolved over time on many systems as the prevalence of the devices dictates different desirable operating characteristics. For example, many early grid codes call for all devices in large areas to automatically disconnect during system disturbances for the safety of local maintenance crews. As penetration levels increase, simultaneous disconnection of all devices can exacerbate system disturbances. Instead, grid codes should be designed to require wind and solar generation to positively contribute to system stability.

Distributed generation also brings challenges at system level. At low penetration levels, distributed generators are generally connected according to the so-called "fit and forget" approach, i.e. treating them as "negative loads". [19] However, as penetration levels increase, operational problems start to appear. These aspects include high- and low-frequency cut outs, and low voltage ride through schemes that may represent reasonable requirements at lower penetration levels, but can cause significant problems at higher levels by exacerbating grid problems, or introducing instabilities by simultaneous disconnection of large populations of units[14]. A recent example is the case of disconnection settings for distributed generation: the "fit and forget" design approach typically proposes higher sensitivity for the frequency settings for disconnecting distributed generation with comparison to the settings of large central units. At higher penetration levels, this approach would mean that large population of distributed generators would be disconnected at the same time, which would pose a security threat to the system (see text box on Grid Codes).

Despite these challenges, integrating lower levels of renewable generation can be done with relatively minor adjustments in system operations and operating requirements. Implementing thoughtful changes at this stage such as updated grid codes and a systematic evaluation of the value of flexibility, can lay a stronger foundation and avoid potential issues that can arise at higher penetration levels.

[13] See for example: [27], for an analysis of integration challenges in the area of Schleswig-Holstein in Germany, experiencing some of the highest penetration levels of wind in Europe.

[14] See for example: [26], for a description of the impact of Germany's solar PV inverter settings on the potential for gigawatt-scale generation losses triggered by relatively low frequency excursions.

3.2 Challenges in the Mid-Term, Penetration in the 50% Range – the big leap

As dependence on renewable energy grows towards 50%, the need for, and benefits from further changes to power system operations become paramount. In general, the needed changes relate to harnessing as much flexibility out of the existing power system as possible. Because flexibility has not historically represented a limiting factor in power systems, much of it is not currently made available to system operators or markets. Sources of untapped flexibility in existing systems can be grouped into six main categories:

1. Market Incentives and harnessing available flexibility.
2. Demand side flexibility
3. Managing distribution grids.
4. Transmission Network changes.
5. Market and System operations challenges.
6. Energy storage.

Each of these categories involves a rich set of measures, each of which may entail implementation challenges. Many of the challenges relate to establishing or improving markets to provide adequate incentives for the needed measures. At the outset, utilities and market operators may not start out having fully evaluated the costs of variable resource integration, or the benefits from measures available to reduce those costs. A first step in addressing the challenges is a thorough evaluation of renewable integration costs and their causes.

3.2.1 Market Incentives and Harnessing Available Flexibility

Markets have a very significant role in ensuring all cost-effective flexibility in existing power systems is made available. Modern power systems rely to a great extent on the energy storage capabilities inherent in hydro reservoirs, natural gas pipelines and fields, and coal piles. Providing market incentives to all generators for a wide array of grid support services is key to accessing all economic storage capability in the existing power system. Reaching the mid-range penetration levels will almost certainly require ensuring that markets and market prices exist for flexibility. Markets would need to be robust enough to provide the appropriate price signals to potential market participants and to define new services tailored to new market participants[15].

For example, one of the primary contributors to the cost of integrating vRES is the need for reserve generation to make up potential shortfalls from scheduled generation, as previously indicated. Reserve generation capability has historically been provided by conventional power plants. However, as variable generation increases, it is likely that the historical sources of reserve services will not be sufficient. Bringing the most cost effective sources of reserve capability to the system hinges on markets providing clear and consistent pricing signals to other potential sources.

[15] Unfettered markets are prone to boom and bust cycles that could lead to reliability issues in the grid if flexibility resources are in short supply. Market prices may need to be carefully managed by reliability-responsible entities or regulators. Mechanisms such as capacity payments to ensure the availability of certain products may be necessary.

Another important market/network reform is to expand markets over greater geographic regions, allowing access to more potential sources of flexibility and averaging system variability over a larger array of vRES. This latter point is important because the overall need for flexibility generally increases more slowly when diversified variable resources are added to the system (i.e. technologies utilizing different prime energy movers or combination of resources from different weather regimes).

Occurrences of zero or negative wholesale market prices need to be available to potential retail market participants. In most systems, the state of wholesale electric markets is not reflected at the retail level, appropriately insulating retail customers from wide swings in wholesale market prices but also isolating retail markets from potential opportunities. Some mechanism is needed to organize potential uses of the occasional surpluses of renewable energy. In particular, there appear to be examples of potential purchasers of low cost, but irregularly available surplus power. One example is using electric resistance heat to supplant industrial fossil-fuelled boilers. Electric boilers are relatively inexpensive and allowing some commercial and industrial customers access to low cost wholesale energy would increase the cost effectiveness of the system and reduce carbon emissions from fossil boilers.

Harnessing flexibility at the distribution system level presents institutional issues. Many generators interconnected with distribution systems are not fully visible or controlled at the system level, and most have no economic incentive to respond to either system level or more local distribution level flexibility needs.[16] Moreover, coordinating and optimizing between system level and distribution levels needs is an institutional challenge of its own.

Expanding market incentives to more participants plays a vitally important role in providing system flexibility as the penetration of renewables increases and flexibility from traditional sources becomes insufficient. In most systems, the untapped flexibility represents a significant source of new flexibility, but accessing it will require extending appropriate economic incentives to resources that have not historically participated (especially from Distributed Energy Resources). Extending markets and incentives over larger geographic regions is another important step toward making most efficient use of existing resources. In most cases, extending incentives to all resources goes hand in hand with market structural changes described in more detail below.

3.2.2 Demand Side Flexibility

There is a growing appreciation of the potential role of energy demand in providing flexibility to the power grid. It is important to open markets to end-use loads and to encourage their participation. In many cases the only needed encouragement may be appropriate price signals. However, in many cases neither the conventional participants in electric markets, nor the end-use loads may be aware of the need for, and benefit of having participation from the demand side of the meter.

[16] A special category of generators falling in this group are dispatchable stand-by generation resources attached to critical infrastructures (Data Centers, Hospitals, Hotels etc). In developing countries the share of such standby resources is very large and could be used as a dispatchable (spinning reserve) capacity to address the variability of vRES.

Encouraging end-user participation may require developing new incentives and programs sponsored by utilities or other entities, and may most effectively be packaged with other services of interest to end users such as greater information about their energy usage, finer controls on energy consuming devices and energy efficiency measures. Demand side aggregation entities may be necessary to work with the many, smaller end-use customers to develop these new sources of flexibility and present them in utility-scale blocks to markets and system operators. Bridging the cultural divide between consumers, suppliers and grid operators is a significant challenge in many systems.

Examples of important sources of demand side flexibility include uses that involve a natural storage component. For example, municipal water pumping or irrigation loads where there are intermediary reservoirs that can be used to decouple the timing of the need for water from the need to pump the water. Thermal storage in insulated water tanks (e.g., hot water heaters and chillers) and insulated building envelopes for heating and cooling systems are other potential demand side flexibility opportunities. It is common for heating and cooling units to cycle randomly to maintain temperatures within a narrow band, but the cycles could be controlled and timed to support needs of the power grid. New and growing opportunities for demand side energy storage include coupling the power sector to the transport sector (electric vehicle charging)[17] and to the heating sector (new heat pump technology coupled with insulated hot- or cold-water tanks)[18]. District heating and cooling systems with thermal storage such as the ones existing in some cities, large corporate campuses, military bases, hospital complexes and university campuses represent largely untapped sources of demand side energy storage in many areas of the world.

An important feature of the demand side is that it tends to be located on lower voltage distribution grids. This fact introduces both potentialities and challenges that are different from high voltage transmission grid resources. An advantage is that the resources can respond to both grid-wide flexibility needs and local needs. For example, local storage can avoid costly infrastructure investments in substations, or even transmission upgrades. One challenge is that devices located on the distribution level often lack communication and controls necessary to help support grid-wide needs and markets. Another advantage is that many demand side devices can respond more quickly than large power plants, effectively reducing the gross capacity needed for some purposes[19]. Finally, demand management can reduce the need for transmission infrastructure investment and reduce transmission-related energy losses.

Depending on demand resources for flexibility products is facilitated when markets allow a diversity of products. Different demand resources may be dependent on time of day, frequency of use, duration of use, and seasonality. Markets requiring a single, high standard of deliverability instead of multiple products can effectively exclude significant demand resources.

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[17] See reference [35] for an analysis of the value of electric mobility as demand response in power systems and the results of the Green eMotion project [34] for the current status on how electric mobility can support the system operation.

[18] See [33] for an analysis of the potential of use of building stock equipped with heat pumps as energy storage in the German system.

[19] For example, if 100 MW of response is needed in one minute, it would take 500 MW of reserves from generators capable of providing just 20 MW per minute of response. In the alternative, it could take just 100 MW of reserves from faster-acting resources.

Demand resources will play a significant and crucial role in systems operating at high penetration levels of variable generation. Most systems today have not fully developed the available potential, and doing so may require new programs and incentives for both end users and distribution system operators. Managing distribution system resources, designing end-use programs and incentives, recruiting end users, aggregating resources are all significant challenges that need to be met.

3.2.3 Managing Distribution Grids

The huge number of units that need to be controlled and communicated with presents a key challenge for systems increasingly reliant on distributed energy resources. This two-way communication and control infrastructure is a new element that needs to be in place to enable the transition to active distribution networks, involving investments but also a new paradigm in system operation. One aspect of the challenge is optimizing the operation of generators, loads, and storage devices to the satisfaction of end users, distribution system operators, and the larger power system. Finally, it is unclear what institutional framework is best suited to operating the devices. In most cases, appropriate institutional frameworks do not exist.

Today's distribution system operators are primarily concerned with ensuring the reliable operation of distribution grids. Their primary planning and operation role involves understanding local uses of the grid and undertaking investments necessary to ensuring its continued reliable operation. There is typically no responsibility for providing services back to the transmission system operator. Although distribution systems are increasingly accommodating generation and storage devices, their role has largely remained reactionary. It may be necessary to envision a new role for distribution system operators taking on a greater responsibility for system-wide services and closer partnership with transmission system operators-- especially necessary to realizing the flexibility potential of distributed energy resources. Coordination among transmission system operators, distribution system operators, and aggregators will be necessary to realize the potential of all demand side resources.

The changing role of distribution system operators likely will require a change in how they are regulated. Regulators commonly allow regulated rates of return on distribution system capital expenditures. Relying on demand side resources can obviate the need for capital expenditures, lowering total costs, but leaving the distribution system operators with a disincentive to participate. Regulators need to consider changing the return structure for distribution system operators.

The increasing complexity envisioned for operating and optimizing distribution system components is envisioned as an important aspect of the Smart Grid concept. Smart Grid is an emerging field that is vitally important to the economic use of available flexibility. However, it also brings additional challenges such as the critical issue of cyber security, because millions of electronic devices are inter-connected via communication networks throughout critical power facilities, which has an immediate impact on reliability of such a widespread infrastructure. [20]

3.2.4 The Role of Transmission Networks

Transmission network-specific changes include building any necessary transmission to access the variable renewable generation (often located in remote areas), and transport it to where it will be consumed. Furthermore, cross-border or continental scale backbone transmission reinforcement is sometimes needed for achieving the benefits from merging of larger geographic areas to common market zones and integrating higher shares of variable renewables.[20] There are usual challenges associated with transmission build-outs, including social acceptability of new lines, environmental impacts and costs. These are not new challenges, but easing the way for development of transmission network expansion may be necessary, and especially challenging in densely populated regions.

Alternatively, solutions should be implemented that allow using existing infrastructure more efficiently. The key strategies on this are presented below:

Power flow control- The most efficient use of transmission resources is also limited by lack of control over network flows. In most cases, making more efficient use of existing transmission is a much more cost effective way of increasing the ability of the transmission grid to accept variable renewable generation, than investments in building out the grid. To achieve this, power flow control devices such as phase-shifters, HVDC lines and FACTS should be installed and be incorporated in the transmission system planning and operation. Incorporating power flow controllers in highly meshed networks with changing flow patterns due to variable resources is a challenge on its own and presupposes accurate and dynamic estimation of the network state. Improper settings of such devices can lead to adverse impacts to the grid and deterioration of the system security.

Dynamic assessment of transmission capability- In many cases, transmission capability limits are derived from infrequently performed static transmission capacity studies. These studies are usually based on worst-case conditions (e.g., high demand and high temperatures) that can be overly restrictive much of the time, or inappropriate when considering variable generation sources. Dynamic line rating allows a more efficient use of existing network infrastructure. Operating the transmission system based on dynamic, close to real-time, collection of system data, is a key component of the Smart Grid concept.

A market aspect related to efficient use of transmission is more geographic specificity to market prices. Uniform market prices over large areas imply a "copper plate" zone where the transmission system characteristics are not visible to generators. This often leads to transmission system congestion, that is resolved by re-dispatching generation units. Nodal pricing[21] reflects local effects of transmission conditions, helping to provide signals for operation of generators and to identify where to best locate new generation, transmission expansion, and energy storage devices.

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[20] A typical example here is the case of Europe, where large-scale deployment of variable renewables translates into a 'sandwich' where variable RES are mainly in the North (wind energy) and in the South (solar energy) while importing load centres are located in the central regions.

[21] Markets with locational marginal ("nodal") pricing provide separate pricing at each relevant point/area in the power system. Locational prices can provide price signals that better reflect the relative value of generation in specific locations, as well as provide appropriate incentives for solutions to local congestion.

3.2.5 Market and System Operation Challenges

The first step to tapping available flexibility is for power markets to trade on a sub-hourly basis. Many power systems have started dispatching generation over 5-15 minute periods, opening up the ability for power plants that formerly controlled power output just once and hour to adjusting output on a much more frequent basis, and increasing the scheduling accuracy of variable generation.

In some cases, finer geographic market delineations could be beneficial. Although flexibility is often looked at as a system-wide need, there can be locally important needs that differ from system-wide needs. This can occur for example in transmission-constrained regions with high build-out of variable generation where local storage could have higher value locally, than it would if viewed from a system-wide perspective. Markets with zonal or nodal pricing can provide the price signals needed to uncap and incentivize locational flexibility potential.

There is a relatively large number of market and system operation characteristics that affect the need for and cost of flexibility. Some key characteristics include:

- **Dispatch Frequency–** Shorter operating periods and more frequent generator set-point adjustments better utilizes available flexibility.
- **Gate Closure Times–** Minimizing the time between when power schedules are due and the beginning of the operating period reduces the need for reserve resources to provide flexibility.
- **Variable Resource Provision of Grid Support Services-** Large penetrations of vRES will require grid services such as frequency response, imbalance service, and contingency reserves to be shared among all resources.
- **Variable Generator Power Management:** Systems in place to control variable generation as needed to contribute to system adequacy, reliability, and security.
- **Ability of Variable Resources to Participate in Day-Ahead Markets.** Some markets impose penalties for underperformance that effectively exclude vRES from the bidding process, substantially increasing the cost of accommodating vRES.
- **Allowing Negative Price Bidding-** Allowing negative market price bids presents appropriate price signals for more efficient dispatch and new energy storage**.** In particular, due to shutdown and startup constraints and costs, inflexible baseload units continue producing during such events, incurring short-term loss of revenue. Flexible units do not face such problems and energy storage can actually increase its revenues by charging during these events.
- **Imbalance Settlements and Penalty Structures-** Variable generation cannot perform as closely to generation schedules as more controllable generation. Punitive imbalance charges and penalties can unduly raise the cost of integrating variable generation**.**
- **Ancillary Services Market Structure**—the extent to which all resources (including demand) capable of providing services can do so. Ancillary markets that accept a diversity of products are more conducive to acquiring available flexibility than markets that require uniformity in produces (e.g., duration and frequency of response).

- **Appropriate Minimum Bid Sizes-** High minimum megawatt requirements for bidders makes it difficult for smaller, distributed resources to participate. Aggregation can help, but very high bid size requirements makes the job of the aggregator more difficult.
- **Variable Resource Forecasting System-** the extent to which forecasts are made and incorporated in system operations and establishing market prices.
- **Variable Resource Ramp Forecasts-** the extent to which variable resource ramping events are forecasted and included in system and market operations.
- **Provision of Peak Demand Adequacy-** Extent to which variable resource contributions are appropriately valued and incorporated into system planning and operations.
- **Incorporating Demand Management–** Demand-side resources are often the least cost source of system flexibility.
- **Cross Balancing Area Trading and Provision of Ancillary Services**– Effectively enlarging power system operations and markets across wider geographic regions reduces the total need for flexibility.
- **Capacity Market Structure-** Ensuring that needed resources are not prematurely retired and that new resource additions receive appropriate incentives.
- **Treatment of Energy Storage-** As both consumers and producers of power, energy storage can be subject to adverse treatment in several ways. For example, as an energy consumer they may be subject to consumption and carbon taxation and interconnection charges, and at the same time subject to additional interconnection charges as generators. Transmission and distribution system studies need to take into account the expected use of the facilities to relieve congestion and not add to it.

This somewhat daunting list is an indication of the extent to which system and market operating practices can affect the need for flexibility. Implementing the host of changes available to reducing the need for flexibility represents a significant institutional challenge.

Although most power systems with more than a few percent of power coming from vRES have begun implementing some of the available improvements, there are likely no systems today that do all that is possible to minimize the need for flexibility. A big part of the reason for that is simply that the need for flexibility has not required all of the available measures. As the level of variable generation increases and the availability of flexibility declines, these relatively low-cost steps will become more attractive to implement.

Although the long list of operational changes represents a significant challenge, it also represents considerable opportunities. Planners and policy makers will want to seriously consider beginning to implement the needed measures before the need for flexibility becomes critical.

3.2.6 Energy Storage

Energy storage is another important source of power system flexibility. Market improvements that better recompense for flexibility will elicit more energy storage available in existing infrastructure such as the natural gas system, coal piles, and hydro reservoirs as previously discussed. While it is common to think of energy storage in terms of devices that receive electric power from the grid and return electric power to the grid, those are not the only options (see text box). Energy storage can occur at the primary energy input level (e.g., storing water in hydro reservoirs), at the grid level (e.g., batteries, pumped storage, etc.), and at the end user level (e.g., hot water tanks, electric vehicles, ice storage, etc.). In this respect, it is important to take advantage of all aspects of economic energy storage.

An important feature of higher penetration renewable energy is the challenge of making the most efficient use of occasional periods of generation in excess of local, or even system-wide demand for electric power. When this occurs, other generation is idled to the extent possible, exports to other regions are maximized, and any remaining variable renewable energy generating capability is simply wasted. These events are accompanied by low, or even negative wholesale electric market prices. Energy storage has an increasingly important role to play as penetration levels increase and along with them, incidents of potentially wasted energy that could otherwise be usefully stored.

Dedicated energy storage[22] additions in the form of batteries, pumped hydro storage, compressed air, or other new technologies likely does not need to be implemented to accommodate the intermediate level of renewable penetration in many systems[23]. Systems with large fractions of generation coming from baseload units and isolated systems will generally find energy storage of greater value.

Although dedicated energy storage may not be needed in the mid-term for many systems, pursuing it even in the near-term makes sense for a number of reasons. Energy storage provides multiple values to the grid that are not entirely recoverable in existing markets. Some studies have found system-wide economic benefits to the introduction of energy storage that cannot be recovered from existing markets. For example, studies in California showing system-wide benefits to storage resulted in a state policy directing utilities to acquire energy storage. Energy storage can also be cost effective in certain niche applications in the near term. Strategically located energy storage may avert the need for transmission or distribution system infrastructure investments. Combinations of values, such as participating in energy markets and averting other infrastructure investments can be an economic choice. In the mid-term, many power systems will find it difficult to justify adding dedicated energy storage solely to provide flexibility, but in combination with other value streams it may be found economic[24].

Secondarily, it is important to continue developing energy markets that will allow multiple value streams for assets like energy storage and support technological development for energy storage to increase its competitiveness. Dedicated research and development is needed in early stages to pave the way for storage that is necessary to accommodate the highest levels of renewable energy penetration as discussed further below.

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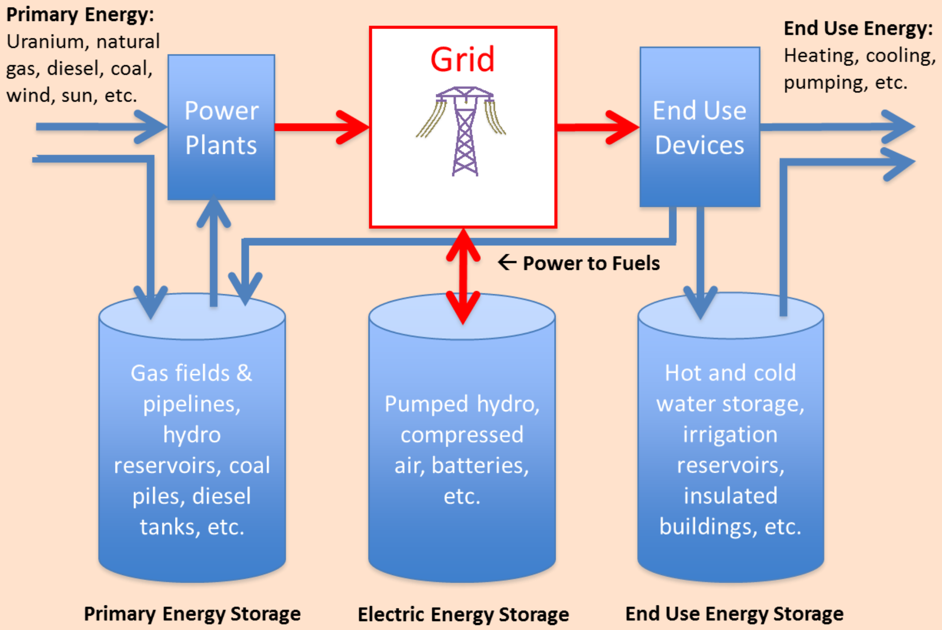
[22] The term "dedicated energy storage" is meant to denote energy storage for the purpose of absorbing and releasing electric power and not incidental to other purposes.
[23] See for example the All Island Grid Study [37]. The study suggests that more than 50% of Ireland's power consumption could come from wind energy without added storage, by simply displacing fossil generation.
[24] This was the case in California where studies considering multiple value streams from energy storage showed a net benefit. See [29].

Generalized View of Energy Storage

Most people associate energy storage with batteries and pumped hydro storage. These technologies take energy from the grid in the form of electricity and return it as electricity. In a broader sense, energy storage corresponds to a shifting of energy production and consumption in time. In this respect, there are two other important energy storage techniques that are less often considered. First is the storage of primary energy sources such as natural gas in gas fields and pipelines, diesel in storage tanks, and water in hydro reservoirs. The other energy storage techniques involve storing end use energy such as hot or cold water for heating and cooling, or irrigation reservoirs. Although these techniques do not generate power back into the grid, they enable valuable flexibility in shifting the time when electric power is consumed. All three techniques are important sources of flexibility.



3.3 Long-Term Challenges, Very High Penetration Levels

Once the flexibility in the existing systems is harnessed, reaching even higher levels of penetration requires addressing three main challenges:

1. Providing energy over longer periods (weeks to months) when renewable generation may be largely unavailable due to prevailing weather conditions.
2. Making efficient use of energy during high production times (e.g., limiting wasted energy).
3. Stable operation with non-synchronous devices— operating a system primarily from a combination of renewable and demand resources.

3.3.1 Supplying Power During Low Output Level Events

Actions taken to fully utilize existing system flexibility will not be sufficient to address sustained periods of low renewable resource production. Extended periods of low wind and low sun can occur even across interconnected regions spanning hundreds of kilometers. Ensuring service reliability under these difficult conditions is perhaps the central challenge in reaching the highest levels of renewable penetration, and places additional emphasis on energy storage.

Conventional energy storage technologies available today such as batteries, pumped hydro storage, and even compressed air energy storage are not likely to fill the need. Hydro and compressed air energy storage require geographic conditions that are not available in sufficient quantities in most areas. Mass energy storage in today's battery technology is not economically feasible. Either some new technology, or technology breakthroughs will be needed to produce the quantities of energy storage and power necessary to fill in for days or weeks of low renewable resource availability. Barring such improvements, other approaches are necessary.

A likely cost effective approach will rely on conventional fossil power plants burning unconventional fuels. These fuels may be biologically based from algae or derived from plant oils such as biodiesel. For example, many natural gas power plants can burn bio-diesel today with little or no modification—some even have fuel tanks to supply liquid fuels in lieu of burning natural gas. It is unclear whether sustainably produced biofuels will be available in large enough quantities to fill the need, but it is one possibility.

Another low-carbon solution is producing synthesized fuels from renewable electric energy. For example, it is a fairly straightforward process to create hydrogen by splitting water into hydrogen and oxygen using electricity as available from renewable sources. The resulting hydrogen could be stored directly and serve as power plant fuel as needed, or else injected into the natural gas system for storage and mixing with natural gas. Hydrogen can be mixed with natural gas (a small amount of hydrogen is a common constituent of natural gas) up to several percent without modification of either the storage and delivery infrastructure or the burners.

Taking this hydrolysis process one step further, methane can be produced[25]. Although the added step increases the cost and reduces the efficiency of the process, methane is the primary constituent of natural gas, opening up the possibility of leveraging existing natural gas storage, delivery, and power generation infrastructure. That advantage may overcome the additional cost and lower efficiency of the process. In effect, this would allow the power system to operate largely as it does today—relying on solar and wind power when sufficiently available, and filling in with conventional generation fueled by synthetic methane when needed.

[25] This process consumes carbon to produce methane—the carbon could come from biomass or from carbon dioxide derived directly from the atmosphere.

3.3.2 Efficient Use of High Output level Energy

Supply of generation in excess of local demand is a significant issue at moderate renewable penetration levels, but becomes a serious economic issue at very high levels. To some extent, this issue can be mitigated by providing market incentives to renewable generators for reducing fluctuations (ramps) and keep more constant levels of output. Solar inverters and wind turbine blade sizes can be selected for more constant output levels (higher "capacity factors") at the expense of energy output. For example solar panels can be (and are in some markets) oversized compared with the inverters used to supply the power to the grid. The effect is to allow the plants to come to full output earlier in the morning, and stay at full output later in the evening. Similarly wind turbine blades can be oversized, so that generator output reaches a maximum at lower wind speeds and therefore operating in a more stable manner, at maximum output levels over more hours of the year. These techniques come at the expense of exploiting a smaller fraction of the available sun and wind energy. They are less likely to occur where the economic incentive for the output is solely the amount of energy produced.

Another strategy is to embrace the occasional over-supplies of electric energy to displace energy use in other energy sectors, and provide price incentives for energy storage devices (electric, thermal, chemical, etc.) that may be able to take advantage of periodic episodes of low-cost electric power available in the market. To date, much focus has been on how systems depending on renewable energy operate reliably when the resources are unavailable, but an almost equally important issue will be how to make best use of energy in excess of immediate demand.

For systems where a substantial amount of the variable generation is interconnected to distribution systems, the challenge and potential solutions become local. These surpluses are most easily addressed by limiting local output, but at high penetration levels more efficient use of the local surplus needs to be encouraged.

3.3.3 Stable Operation with Non-synchronous Generation

Grid support services include reactive power support, frequency support, contingency reserves, balancing services, black start capability. In very high penetration levels, the market value of system services will constitute a key value stream for market participants, whereas the wholesale market value of energy will be diminished due to the abundance of low cost renewable electricity. Today, few systems require or allow these services to be provided by vRES and are primarily provided by conventional generation. However, at very high levels of penetration, a significant portion of these services will need to come from variable generation. Other sources include demand-side resources and dedicated energy storage. Using variable generation to provide grid support services necessitates forgoing a portion of the renewable generation, and one of the challenges will be providing sufficient price incentives, or other directed requirements to supply the needed services.

Although developing a full set of "future-proof" code requirements is an active area of research, systems that face higher penetration levels of variable resources already develop more advanced grid codes to enable a more active participation of inverter-connected generators to the system. A good example is the power-frequency response requirements introduced in the Irish Grid Code (EirGrid

Code Version 5.0, Figure 3) where wind power plants are required to provide frequency support services. As can be seen, outside a frequency dead-band (FB-FC) the code requires wind generators to contribute more of the available generation as frequency drops, and to curtail production as frequency increases. To allow the option of ramping up, wind turbines should be operated in a reduced generation mode (e.g., normally producing 90% of the available wind energy) which translates to production losses.

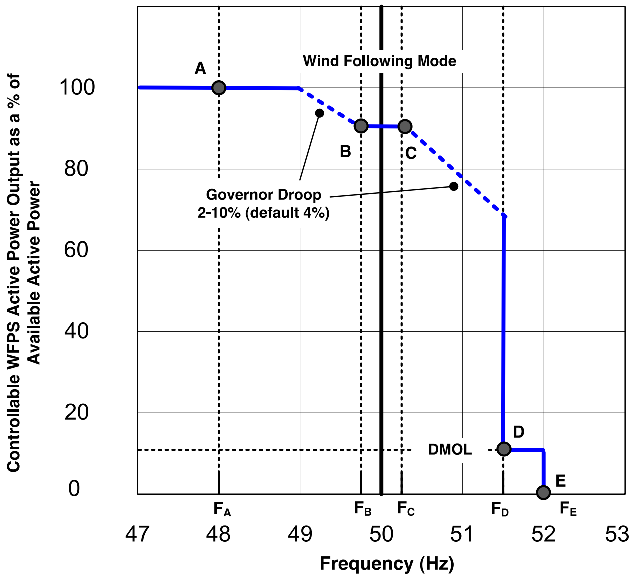


Figure 3 Power-frequency response requirement in Irish Grid Code (EirGrid Code Version 5.0).

Another key challenge is how to maintain stable operation with little or no synchronous resources. [21] Operating a power system means balancing power generation and loads at any moment; imbalances contribute to power system frequency deviations that can lead to instabilities[26]. Frequency excursions that cannot be balanced by the primary reserves trigger corrective actions such as load shedding when demand exceeds generation, or involuntary curtailment of resources when generation exceeds demand. Uncontrolled deviations from the frequency setpoint may lead to disconnection of large population of units and potentially to system collapse.

The kinetic energy stored in the rotating masses of generators and loads, i.e. the power system's inertia, determines how sensitive the system frequency is to supply and demand imbalances. Higher power system inertia means that the frequency is less sensitive to temporary imbalances. In the very first moments after the loss of a generating resource, the inertia of the rotating machinery helps to limit the drop of system frequency. The braking torques associated with decelerating of the generators release some of the rotational energy stored in the equipment. This results in additional instantaneous power output from the synchronous

[26] The rotational speed of synchronous generators is directly tied to system frequency; in case of excess generation the generators spin faster and system frequency increases; when demand exceeds generation, generators spin more slowly.

machinery supporting the system, even before primary reserve is activated. In the case of synchronous generators this power boost may amount up to a multiple of the nameplate capacity.

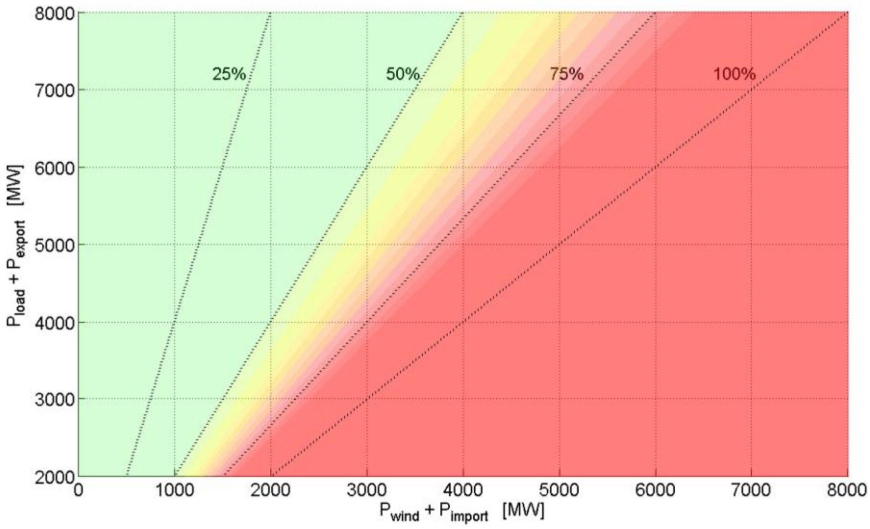


Figure 4: Indicative illustration of the allowable operational range of the 2020 All Island Power System based on [21]. Dashed parameter lines indicate penetration of wind generation based on net load. Left area (green): no relevant technical issues. Lower right area (red): technical issues jeopardising stable system operation. Range in between (yellow): transitional range, technical issues become increasingly critical. Ranges may be changed or reduced by future studies.

Most variable renewable generators are not synchronously coupled to the system frequency. They are equipped with electronic power converters and the torques are controlled by computer and the frequency of the system is decoupled from the rotational speed of the generator. Hence, they do not contribute to the inertia of the system but rather replace synchronous units and reduce the system inertia. An increasing share of variable resources may therefore make the system more vulnerable. As shown in Figure 4, for the Irish system, the maximum allowable share of non-synchronous instantaneous generation inertia lies in the range of 60%-80%. In order to reaching higher shares of variable renewables, specific actions should be taken to ensure that there is sufficient inertia in the system. Key strategies for tackling this challenge is to enable converter-connected units to provide inertia, or keep synchronous units online for provision of system services (synchronous condensers[27]).

The electronic power converters in different types of units such as variable renewable generators or energy storage generally have capabilities that could be exploited for supporting the system inertia. However, the operating characteristics of converters are not standardized, their full functionality rarely exploited, and rules for how they should be made to interact with the grid are not fully in

[27] A synchronous condenser is a device identical to a synchronous motor/generator, whose shaft is not connected to anything but spins freely. Its purpose is not to convert electric power to mechanical power or vice versa, but to provide services to the grid

place. Despite the uncertainties, there are good indications that solar and wind resources can provide the needed services although further research and development is needed [8].

Synchronous condensers are dynamic controllers of reactive power which however due to their rotating mass provide inertia to the system. Their spinning rotor's mechanical and electromagnetic inertia, which make the machines more tolerant of grid disturbances, is exactly their key advantage over power electronic devices such as static VAR compensators. As discussed in [22], new synchronous condensers remain 10 to 20 percent more costly per VAR of reactive power capacity than an SVC. But repurposing old power-plant generators upon decommissioning and transforming them to synchronous condensers can be a quick and cheap solution. This is a strategy that is expected to be used in the future to tackle the inertia challenge.

3.4 Flexibility challenges – key takeaways

The challenges emerging from the integration of vRES in power systems can be roughly categorized in 3 regimes:

1. In the **near-term regime** (vRES penetration levels starting reaching double digits), a number of challenges start to emerge signalling issues that become more evident at higher penetration levels, such as the need for holding reserves for up-regulation, and the incorporation of distributed generation. Despite these challenges, integrating lower levels of renewable generation can be done with relatively minor adjustments.
2. As penetration levels reach the 50% range (**mid-term regime**), changes are needed, to enable harnessing as much flexibility out of the existing system as possible, in the key categories of markets, demand, distribution grids, transmission grids, system operation and energy storage. In this stage the large-scale transformation of the system takes place and the foundations are laid for the transition to extra high penetration levels
3. Once the flexibility in the existing systems is harnessed, reaching even higher penetration levels (**long-term regime**) requires addressing three main challenges, namely a) Ensure supply for periods of energy scarcity (weeks to months) due to unavailability of renewable generation, b) Making efficient use of energy during times of over production (e.g., limiting wasted energy) and c) enable stable operation of the system with non-synchronous devices.

These three regimes provide the natural path that a system needs to cross towards the goal of 100% vRES penetration. To tackle these challenges, specific actions should take place at the right time. The next chapter presents the set of needed policy and institutional frameworks to enable the transition in each regime.

4 Policy and Institutional Frameworks

Although the technical challenges of finding and exploiting enough flexible resources is manageable at fairly high penetration levels, the institutional challenges may be far more daunting. For example, distributed sources of flexibility technically available from end-users and distributed generation will need intensive programmatic efforts to recruit and fold the resources into normal power system operations. Opening markets to these system participants will help, but it is likely that policies will be needed to fully integrate end-users into power markets to provide the needed flexibility.

Similarly, incentives to renewable generators to forego generation to provide grid support services will require significant changes in existing policies in many parts of the world. Changes to reliability standards may also be necessary to allow flexibility contributions from non-traditional (e.g., demand-side) sources. Although moving away from conventional resources for providing grid support services, transitioning to reliance on a combination of vRES, demand management, and energy storage may be technically and economically achievable, it represents a major transformation in the way power systems are planned and operated today.

Ushering in a transformed grid to economically accommodate large penetrations of renewable energy represents a daunting institutional challenge. Incentives need to be developed and no doubt adjusted through time. Grid codes and technical capabilities of variable generators need to be advanced and researched. Incentives for the proper location of new vRES, and the development of appropriate and economic transmission and market expansions must be developed. Orchestrating the needed institutional changes in a timely manner is probably more difficult than the technological challenges.

Reaching a carbon neutral power system with sufficient flexibility to provide a safe, secure and economic power supply will take the resolve of all power grid stakeholders—including regulatory and governmental bodies, utility managers and planners, customers, and researchers. That resolve will be tested in the near-term as policies and institutional frameworks are needed now to lay the foundation for the transformation to come. Some of the policies and institutional changes needed are outlined below. While the main challenges are in the mid-term and long-term, short-term action is needed to bring the policy and institutional frameworks in place to anticipate the significant changes ahead.

4.1 Near-Term

Near term policy recommendations refer to the policies needed for systems that are in what we call the 'Near-term regime' i.e. low vRES penetration levels. Such policies are designed to reduce the cost of accommodating modest vRES penetration levels and to pave the way for more significant changes needed at expected higher penetration levels. Focusing on these policies has special relevance since most of today's power systems are in this development stage. The policies described in this section are summarized as a checklist in Table 1 and focus of two key areas, namely to minimize conventional generation reserve costs and to lay foundations for the mid-term challenges.

4.1.1 Minimize Conventional Generation Reserve Costs

Expanding Sources of Reserve Services

Flexibility requirements show most prominently as the need to hold reserve generation to cover unplanned deviations of vRES generation. Although variability and unpredictability are key characteristics of vRES, power systems operating and market procedures were not developed with these unique characteristics in mind and relatively minor changes can significantly reduce the need for and cost of reserve generation.

Opening markets for reserves to a wider range of participants and to larger geographic areas is key to reducing the cost of providing those reserves in many systems. This can be an important and relatively straightforward first step to reducing the cost of reserves needed for vRES. The difficulty of Expanding balancing markets across different systems depends on the level of alignment of the different market arrangements, and can be very complicated if market rules deviate significantly. Reserves can come from different providers and different technologies including, as discussed below, vRES generators themselves and end-use technologies.

Shortening Operating Periods and Gate Closure times

An important initial step for reducing the cost of reserves includes reducing the length of operating (i.e. schedule or dispatch) periods. Most power systems develop a plan or schedule of supply and demand for each hour. Because the deviation from forecasts grows through time, the deviations over shorter time periods are less than longer ones. Reducing the scheduling or dispatch periods to anywhere from five to fifteen minutes can significantly reduce the deviations from plan, and hence, the need for reserve generation to cover those deviations.

Similarly, reducing the time between when a schedule is due and when it begins also reduces deviations and reserve needs. These time periods are called "gate closure" times, and can be as long as two hours in some systems. Reducing the gate closure periods due to less than an hour is a reasonable goal. This however should be combined with measures that address intra-day market liquidity[28], to allow that intra-day markets actually provide enough opportunities to take actions upon updated forecasts.[29] [11]

Quantifying and Valuing Reserves

Reducing the need for reserves is not a sufficient step without an objective, technically accurate means of quantifying the need for reserves. Many systems may use historical experience to derive estimates of reserve requirements. As vRES become a significant driver of holding reserves, more

[28] Markets are defined as liquid if the number of bids and the amount of trading activity is high enough to create transparent prices and ensure that individual actors only have small impacts on the price formation.

[29] As discussed in [31], the key concern when implementing intraday markets is whether both balancing and intraday markets can remain sufficiently liquid. In [32] it was pointed out that lack of liquidity may lead to an inefficiency of intraday markets. The analysis of trading volume for 2008 for Germany and other countries as the indicator for liquidity showed that the intraday markets were not sufficiently liquid. Starting in 2009, TSOs in Germany have been committed to balancing their procurement for uncertainty of wind forecasts through the day-ahead and intraday market, and the liquidity of the intraday markets substantially improved when this new market setup was implemented.

analytically based estimates are needed. A first step for many power systems is developing analytical techniques appropriate to deriving the need for reserves—these must be sensitive to length of scheduling periods and gate closure times to take advantage of the preceding recommendations for reducing those times.

A complimentary need is to accurately value the cost of providing reserves. This is an important first step to developing markets for reserves in which vRES and demand side resources will ultimately participate. Price signals that accurately reflect costs are important to acquiring the most cost effective sources of flexibility available.

4.1.2 Foundations for Mid-Term Policy Objectives

Accessing sufficient flexibility in the near term centers around relatively modest actions taken to reduce the cost of providing needed flexibility. A key feature of policy actions taken in the near term is to prepare for higher penetration levels in the mid-term phase. Each phase needs to take actions to ensure the policies and flexibility needed for higher levels of vRES generation can be put in place as needed.

Reducing Counterproductive Incentives and Penalties

For vRES to contribute flexibility resources, they have to operate below their full potential for the given amount of wind or sun at any moment. As a consequence, for reserves and other flexibility services to come from them, some amount of production will be lost. This lost generation is the cost of providing services from vRES. Economic incentives or penalties that stand in the way of reserves and other services coming from vRES need to be identified and reconsidered. Production credits and above-market feed-in tariffs are examples of policies ripe for reconsideration. These policies have generally been very successful at promoting vRES development, but will need to be phased out to allow vRES to provide reserves and other grid support services that will be necessary at higher penetration levels.

Develop Robust Grid Codes

Processes are needed to determine grid codes that support power system reliability and stability under high vRES penetration levels. In many regions, low voltage ride-through, low- and high-frequency cutout set points, and lack of inverter controls have raised concerns about vRES generation subtracting from grid stability. Appropriate grid codes need to be developed and phased in over time to ensure reliability at high vRES penetration levels. At low penetration levels, these advanced requirements are not mandatory for most systems, but given that vRES can be constructed relatively quickly (and the need for carbon emissions on a similar track), it is important to develop these new codes and standards at an early stage.

Smart Grid Frameworks

As discussed earlier, the concept of the Smart Grid is important to accessing efficiencies in existing infrastructure and is an important component of the transition to higher penetration levels. In the Near Term Regime, research and development is objectives should include assessment of the benefits of Smart Grids, development of demo projects, and analyzing the roles of key market players (e.g. distribution system operators). Although at such low penetration levels, implementation of Smart Grid is not imperative, developing institutional structures and incentives necessary to push forward as necessary need to be engaged.

Develop Dynamic and situational Reserve Requirements

Many power systems have developed static estimates of the need for reserves based on overall load, and vRES penetration levels. However, a more precise computation that takes account of current load and vRES generation levels can free up reserve generation for other purposes, lowering overall costs. The near-term is a good time to begin developing data, analytical techniques and systems to allow more dynamic determination of reserve requirements that will be vital in minimizing costs at higher vRES penetration levels.

Forecasting Systems

Although vRES resources involve a level of unpredictability, standard weather models can provide relevant forecasts that can be incorporated into power system planning and operations. Policies should be considered to develop and integrate the best forecasting techniques into system operations and planning. Forecasts can be used to inform market participants to make the most efficient use of available resources. Numerical weather prediction models need to be "tuned" to provide the most useful forecasts for vRES. Special focus needs to be given to the relative certainty of any given forecast (more uncertainty implies the need for more reserves), and attention given to alert for rapid changes such as fast-moving weather fronts that can affect wind generation over large geographic scales. Instituting communication between power system operators and weather modeling experts can lead to forecasts most relevant to setting reserve requirements, and tailoring the need for flexibility services.

Greater visibility of forecasts and incorporating them into daily and weekly planning is also important to ensuring the power system operates as cost effectively as possible. Some power markets have had difficulty incorporating day ahead schedules into the power planning process due to potential failure-to-perform penalties if the forecast is too high or low. Nevertheless, markets work best with the widest possible sharing of information. It is common practice for power traders and system operators to scrutinize weather forecasts for their effects on demand, it is similarly important for market participants to have similar weather information as it affects generation.

Flexibility and Grid Support Services from VER

As vRES generation replaces conventional sources of grid support services, those services will increasingly need to be provided directly from vRES. Policies for promoting or requiring grid support services from vRES need to be developed in the near-term. This can include revisions of grid codes to require functionality from vRES inverters, removal of contractual penalties that may exist for producing less than the maximum possible generation, and extension of markets to allow vRES generation to provide such services.

Frameworks for Diversity Incentives

Diversifying the sources of vRES generation can significantly reduce the need for flexibility. Generators based on similar technologies (e.g., all wind or all solar) located in close geographic proximity to one another will tend to vary in unison (i.e., are highly correlated with one another), maximizing the need for flexible balancing resources. These effects can be quantified and reflected in the prices paid, or on charges levied on new vRES generation coming on to a system.

Frameworks for appropriately reflecting the value of diversity can begin to be developed in the near term. Such policies may result in identification of geographic resource development zones. Another approach is to adjust imbalance charges commonly levied on generators for production levels differing from scheduled (forecasted) amounts. Imbalance charges for a specific hour can be higher for imbalances that contribute to the net system imbalance, and lower for those that reduce it. This is another way to provide cost-based incentives for encouraging diversity.

An important part of the diversity incentives is the quantification and valuation of flexible reserves previously discussed. It is important to provide diversity incentives that reasonably reflect the value of that diversity.

Planning for Phasing Out Less Flexible Baseload Resources

Less flexible baseload resources (typically conventional coal and nuclear) need to be replaced in the long term by a combination of vRES and more flexible conventional resources. Large fractions of energy being served by baseload generation hasten the need for flexibility from other sources: demand resources, energy storage, and limiting vRES output. New conventional generation needs to provide flexibility (low minimum generation levels, high efficiency over the operating range, and high ramping capability). Cost effective plans need to be formulated and be supported by market design adaptations to retire baseload generation without undue life extensions.

Begin developing market for demand resources—expand demonstrations

At high levels vRES penetration levels, flexibility will be sourced from a combination of conventional resources burning low carbon fuels, selective vRES controls, energy storage, and controlling the demand for power. Of these, demand management is likely the least expensive. As with energy efficiency measures, demand management will take time to develop and deploy. Plans should be formulated at an early stage to undertake demonstration and commercialization programs for demand management. This may need to be spearheaded by regulators providing appropriate incentives for utilities to develop such programs.

Other implementation structures (e.g., third party aggregators and providers) should also be considered. Key issues concerning the role of aggregators should be reconsidered, such as the monopoly position of suppliers with respect to balance responsibility.[30] [6]

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[30] In order to avoid situations where suppliers that own demand and generation are not incentivised to increase the role of demand since it directly competes with their own conventional generation.

Utility Business Paradigm Review

Business paradigms in which utilities receive a regulated return on capital investments on generation, transmission, and distribution infrastructure may not be adequate for developing power systems where power sources (e.g., rooftop solar) and flexibility sources (e.g., end use devices and local storage) are not owned or directly controlled by the utilities themselves. Conversations and experiments in new utility business paradigms need to begin at an early stage.

VER ramp forecasts and Dynamic Reserves

The greatest need for flexibility is when vRES generation levels change rapidly ("ramp") in response to large-scale weather events. Power system operators and weather forecasters have a long tradition of watching weather for threats of temperature extremes (e.g., very hot summer days and cold winter nights). Many power systems today have not fully taken advantage of weather models to forecast extreme vRES events. The near-term is the time to develop systems for producing vRES-relevant forecasting systems and to determine how to best incorporate such forecasts into calculating and acquiring reserves sufficient to the need.

Establishing universal reserve requirements based on extreme events is not the most cost effective use of flexible resources. Instead, a dynamic assessment of reserve requirements is needed, where the needed reserves are defined with respect to the maximum expected forecast errors for each operational period.

RD&D on investigation of key Mid-Term challenges

Funds need to be dedicated to research, development and demonstration (RD&D) activities should be allocated at early stages in the near-term regime, focusing to the investigation of key challenges arising in the mid-term, in the main areas of market expansion and design, demand participation, smart grids, transmission network flexibility and management.

Table 1 Near-term Flexibility Roadmap Policy Checklist

Near-Term Objectives	Near-Term Policy Actions
Minimize Conventional Generation Reserve Costs	• Balancing authorities begin looking to expand the geographic and technological sources of balancing services. • Reducing operating period lengths or developing markets for sub-hourly dispatch. • Begin implementing or considering shorter gate closure times. • Quantifying and Valuing reserve requirements.
Lay Foundations to Address Mid-Term Objectives	• Remove market practices that unduly penalize vRES from full participation in the market (e.g., imbalance penalties, day-ahead under-performance penalties, etc.). • Begin revising vRES incentive structures to reduce penalties for providing balancing services. • Begin developing robust grid codes. • Begin developing institutional and technical frameworks for smart grid.

	• Begin developing dynamic/situational reserve requirements. • Evaluate the benefits and best use of vRES forecasting systems. • Encouraging vRES to provide flexibility and grid support services. • Developing frameworks for offering diversity incentives. • Begin planning for phase out of inflexible baseload resources. • Begin developing market for demand resources—expand demonstrations. • Begin considering new business paradigms for utilities (e.g., decoupling). • Develop vRES ramp forecasts and incorporate into dynamic reserve assessments. • RD&D funding on investigation of key Mid-Term challenges

4.2 Mid-Term

As discussed previously, the mid-term is the time for the biggest and broadest institutional changes occur. Many of the policy options here involve implementation of sometimes-complex measures begun in the near-term. It is imperative to begin the process early, as institutional change is often slow and difficult to advance. Table 2 summarizes the policy measures discussed in this section.

4.2.1 Market Incentives to Promote Greater Resource Participation for Flexibility

Markets have an expanded role in the mid-term penetration levels. System operators must extend acquisition of flexibility services from more technological and institutional sources. These will include vRES operators and demand control—potentially from third party aggregators.

Expand markets for flexibility

Markets are expanded to accept flexibility from more power system participants and technologies. This generally entails short sub-hourly dispatch periods, separate markets for bidding both incremental generation (decremental load) and decremental generation (incremental load), short (e.g., hourly) or daily performance commitment periods, and inclusion of demand-side and storage resources.

Reflect wholesale market prices at the retail level

Higher volatility in power prices is expected as vRES are added to power systems, translated into a succession of low and high power price events. At times of high vRES production, wholesale power market prices will dip below the cost of fossil fuels, while periods of low vRES production will translate in scarcity events and high power prices. To make the most effective use of power in these times of relative abundance or scarcity, policies are needed to allow more potential customers to react to these prices by purchasing power at periods of abundance (low prices) or reduce consumption at periods of scarcity (high prices). This may require new dynamic tariffs that may reflect wholesale market prices to retail level or new energy products for end use customers that would trigger the use of the demand flexibility.

Remove barriers to vRES providing flexibility and grid support

The most cost effective approach to incorporating high levels of vRES will inevitably include selective controls on VERs to reduce flexibility requirements. Contractual relationships between generation owners and power purchasers and wholesale electric market rules need to anticipate the need for the power system to limit output at times without unduly penalizing any of the parties. Power system or market operators need to allow for, and pay for limitations on vRES generation. Similarly, production incentive structures may need to be adjusted to reduce the cost of foregone generation to the projects. [13]

Allow negative wholesale market prices

Negative wholesale market prices are a natural outcome of systems in which there are costs associated with reducing generation below certain levels. Although this can be exacerbated by new vRES generation due to the production incentives, it can occur through several mechanisms (e.g., shut-down and start-up costs) irrespective of vRES production incentives. Reflecting those negative market prices in the market provides incentives for new uses of the available low-cost energy and give a strong de-investment signal towards inflexible units. Allowing negative prices provides incentivize more efficient use of available low-cost energy, bolsters market prices at the low end, and encourages flexible resource additions.

Remove any penalties that unduly restrict vRES participation in markets

Penalties are instituted by system and market operators to discourage egregious behavior that may threaten the security of the power system. Such penalties are generally designed for conventional generators. A prime example of such rules is the prequalification requirements regarding the reliability level for the control reserve capacity bids, which often are 100%. Although this arrangement makes sense for conventional units, it becomes a burden on the participation of vRES generation, for which day ahead generation projections can have errors. As a result, it is more difficult for vRES to bid fully into day ahead markets and subsequent decision-making (e.g., fossil fuel purchases for conventional generation that is ultimately not needed) actually increases overall system costs.

Penalties for participation in markets need to be reviewed and adapted as necessary to provide appropriate incentives for vRES participation.

Implement peak demand contribution assessments for all resources on comparable bases

Power systems must have sufficient resources to meet peak demand with a high level of certainty. Planning reserve margins have historically been used to ensure that the installed generating capability is sufficient to meet demand under high load and (historically) high power plant outage conditions. Planning reserve calculations in this fashion tend to overestimate the contribution from vRES generation. While some power planners assume zero contribution from VERs, the actual contribution from all resources needs to be assessed and properly taken into account [23].

Modify vRES production incentives to encourage diverse deployment of resources

Flexibility requirements for vRES are dependent on the geographic and technological diversity of those resources. This diversification effect relates to three key aspects:

a) *Smoothing of vRES infeeds*: combining different technologies or placement of vRES generators in distant zones reduces the correlations among the generators. The aggregate generation exhibits less variability than generation from more highly correlated generators. [24]

b) *Lower forecast errors*: less correlated generation increases the forecasting accuracy as forecast errors have a greater tendency to cancel one another than the forecast errors for highly correlated generators. This leads to a reduction of the system imbalances and reserve generation. [25]

c) *Reduced congestion*: transmission system congestion affects the location of vRES, often resulting in concentrating many vRES generators in a few locations with available (uncongested) transmission. Concentrating vRES results in highly correlated generators that require a higher degree of system flexibility.. The provision of proper locational signals (e.g. through nodal/zonal pricing) is one way of providing appropriate incentives for the placement of vRES in areas where are more needed for the system and for the development of the network to accommodate these resources.

The relative value brought by specific resources needs to be taken into account in either the purchase of the resulting generation, or to the integration costs charged back to the resources. Examples of alternative approaches is designating technology quotas and renewable energy development zones. However, each related policy decision brings risks and implications related to the reinforcement of already mature technologies (e.g. vRES) in detriment of incumbent ones (e.g. energy storage). Optimally developing high levels of vRES depends on recognizing the diversity value of different variable resource generation.

Implement policies to encourage the retirement of baseload plants

Baseload power plants were generally designed to operate at a constant rate throughout the year (except for maintenance periods). As such, they have less flexibility than generators designed to be adjusted with demand, and tend to reduce system flexibility especially at times when renewable generation peaks (high winds, or mid-day sun). At lower penetration levels, this is not an insurmountable barrier, but as the fraction of generation served by vRES reaches into the double digits, the need to turn down other generation increases. It is therefore prudent to plan for the retirement of baseload generation (primarily coal and nuclear power plants) at the end of their economic lifetimes (usually 30 years).

An alternative strategy for the mid-term is to retrofit baseload plants to provide additional flexibility. That strategy may be economic for newer plants, but ultimately most baseload plants will be retired when reaching the highest renewable resource penetration levels, and the mid-term is the time to begin this retirement planning.

In many cases this can be done by relying to market prices, as long as they can properly reflect the impact of oversupply (e.g. allowing negative prices as discussed above). Power systems were traditionally designed based on baseload units and their retirement could entail additional challenges on system operation and security (e.g. planning of primary reserves) which should be carefully considered at this stage.

4.2.2 Demand-Side Market Participation

Ultimately, flexibility for large penetration levels of vRES generation will come from a combination of the VERs themselves, energy storage, and flexibility on the demand side. The most cost effective of these are likely to derive from inherent flexibility of some power uses. Development of demand-side flexibility resources takes center stage in the mid-term phase.

Frameworks for developing and aggregating demand side management resources

Demand resources are largely found on the distribution grid, characterized by a large number of relatively small (kilowatt-scale) energy consuming devices. Distribution systems owners and operators have not historically engaged these resources to a large degree. Policies are needed to provide distribution system operators or owners incentives to use these resources, and develop institutional structures to support this (e.g., third party aggregators). Regulators may choose to impose requirements to develop demand side resources analogous (in some cases directly so) to minimum requirements for renewable generation or energy storage.

Comprehensive incentives and institutions to develop flexible distributed generation resources

Distributed generation resources provide a range of benefits, including generally reducing the need for high voltage transmission infrastructure and power losses in distribution and transmission grids. Comprehensive policies will provide incentives to both develop these resources and encourage development that provides power system flexibility.

4.2.3 Manage Distribution Grids

The value and importance of flexibility increases with vRES penetration levels, and so does the importance of wringing available flexibility out of distribution grids. Flexibility exists at the distribution system level in both energy consumption and production—both sources need to be addressed. Managing these resources invites policies to incentivise needed institutional structures and incentives to acquire, aggregate and dispatch these resources.

Transition of distributed generation to require communication and control equipment for system dispatch

Most currently installed distributed generation lacks control and communication equipment to allow participation in providing flexibility services. At a minimum, new distributed generation equipment should be equipped with technologies that will allow provision of flexibility services, especially as the costs of communication and control equipment drop to the point where it can be cost effectively installed on ever-smaller (i.e., kilowatt-scale) devices.

Implement aggregation and optimization of distributed generation and demand management

Installing communication and control equipment on distributed generation and energy use technologies is a necessary, but not sufficient condition to their participation in supplying grid flexibility. Each distribution-level device is capable of servicing a number of potentially competing services. Both institutional (including market design) and technological systems need to be developed to coordinate and operate these resources. This is implementation of an important facet of the smart grid concept.

4.2.4 Enhance Transmission Network Functions

Policies for encouraging smart grid investments in the transmission system are necessary to both accessing available flexibility and to reduce the need to add expensive and difficult-to-site transmission infrastructure.

Transmission expansion

The integration of vRES brings significant needs of expanding the transmission system, for two key reasons: a) for the connection of vRES plants that are located in remote areas and b) for the reinforcement of corridors due to the changing power flow patterns. Although transmission expansion is traditionally the first option to consider, building new transmission projects is often met with issues of public acceptance resulting to a low number of realized projects with respect to targets. It is therefore necessary to optimize the use of existing assets and to enhance the controllability of the system power flows.

Implement dynamic measurement, capability assessment, and control of transmission systems

Dynamic control of transmission systems allows grids to be operated more efficiently, allowing greater access to VERs and to generation capable of providing flexibility services while minimizing the need for expensive and difficult-to-site transmission infrastructure. This is an important facet of implementing the smart grid.

Increase geographic granularity of (nodal) market prices

Geographically-specific price signals are important to providing incentives to sources of flexibility to locate where most needed. The finer the geographic scale of the prices, the more likely that local congestion issues can be cost-effectively addressed by cost effective flexibility available from energy storage, generation, or demand resources.

4.2.5 Increase Market Functionality

Relatively minor adjustments in market function are expected to be sufficient to operate systems with modest levels of VERs. As the level rises, it becomes increasingly important to refine market rules and functions to work efficiently with vRES generation

Liberalize flexibility markets to allow bids for shorter time periods

Market policies need to allow for separate incremental generation (decremental load) and decremental generation (incremental load) bids, with dispatch and offer commitments over shorter time periods. For example, wind generation can submit decremental generation bids reliably over periods of thirty minutes with a high degree of reliability when generation levels are high. Demand resources can supply higher levels of decremental demand during higher demand periods. Allowing for short term as-available bids makes more flexible resources available at any given time, reducing overall flexibility needs and costs.

Implement shorter gate closure times (no more than one hour)

Short-range wind and solar generation can be projected far more accurately in the near term future (e.g., minutes to hours) than in the longer term (hours or days). Allowing market bids to be submitted within an hour of the delivery period reduces the difference between the estimated or scheduled generation levels and the actual output. Ths reduces the amount of flexible (and expensive) reserve generation market operators need to hold. Although a significant change in market practices, this step is important to reducing the cost of integrating VERS by reducing the need for flexible reserve generation.

Implement shorter trading/dispatch periods

Similar to the above, output levels of VERs tend to be less variable over shorter time periods than longer ones. Historically, most markets have traded over hour-long operating periods. Either reducing operating period length, or introducing sub-hourly re-dispatch of generation reduces the need for holding expensive flexible reserve generation. Sub-hourly dispatch or operating periods of ten minutes or less should be seriously considered.

Consolidate balancing areas explicitly or virtually through other mechanisms (e.g., imbalance markets) to cover the largest practicable regions

Balancing areas are entities responsible for ensuring power reliability in their systems, in part by directing the output level of generators to maintain balance between generation and demand. Larger balancing areas benefit from two flexibility advantages. First, including a larger number of generators in the balancing area gives access to more potential flexibility. Second, the balancing needs separate balancing areas is larger individually, than the needs when the two systems are combined. This is because the more or less random fluctuations for which flexible reserves are required cancel one another roughly half the time. Combining systems can be done explicitly, or by sharing resources and balancing needs contractually. Policies encouraging combining balancing areas reduce the need for flexible resources.

Flexible resource capacity payments as necessary

While less flexible resources (especially new ones) needs to be discouraged, it is important to ensure sufficiency of flexible resources. This may require careful quantification of the need for flexibility and instituting so-called capacity payments to ensure those resources are not retired and do participate in markets. Regulators may have a role in requiring analyses of the supply and need for flexibility.

4.2.6 Lay Foundations to Address Long-Term Challenges

In addition to the heavy load of institutional changes needed in the mid-term phase, it is also necessary to undertake policies that will make the long-term phase possible.

Begin retirement of inflexible baseload resources

Policies to plan for retiring less flexible power plants undertaken in the near-term phase need to be executed in the mid-term, resulting in shutting down baseload power plants in favor of combinations of demand management, new vRES, and new flexible conventional generation. This retirement process should take into account repurposing of old units and their transformation to synchronous condensers for provision of system services and especially ensure the necessary system inertia levels needed for the transition to higher shares of converter-connected vRES generation.

Begin implementing new business paradigms and regulation for utilities

New business models for utilities and new institutional structures need to encouraged and undertaken in the mid-term phase. This includes a broader mandate for distribution system owner/operators, aggregation of distribution demand and supply resources, optimizers of the use of these resources, and regulatory change as needed to give utilities incentives (or decrease disincentives) for instituting distribution resources.

Implement grid codes capable of operating power systems with high shares of converter-connected generation

New grid codes need to be adopted in the mid-term that are capable of ensuring the combination of VERs and distributed resources are capable of providing reliable and stable power system operations. The grid code development at this stage should already start dealing with the issue of the provision of synthetic inertia from converter-connected variable resources, in order to allow the system operation with higher shares of non-synchronous generation.

Implement best practices for vRES forecasting and use of forecasts in planning and operations

Coordinated use of best practicable variable resource forecasts need to be incorporated in market and power system operations. Forecast accuracy (which can vary depending on prevailing weather conditions) is fully incorporated into power system and market operations.

Implement vRES ramp forecasts and incorporate into dynamic reserve assessments

Advance forecasting tools are implemented capable of informing the need for reserves and flexibility based on forecasts of ramps and overall vRES output variability. These forecasts are incorporated into power system operations to arrange for the needed flexibility, including limiting the output of VERs when economic to do so.

Energy Storage

Policies are in place to assess the full system value of energy storage, and mechanisms for acquiring cost-effective energy storage are implemented. Examples of such mechanisms may be capacity payments or other subsidies and acquisition mandates.

RD&D on investigation of key Long-Term challenges

Dedicated budget on research, development and demonstration (RD&D) activities should be allocated at early stages in the mid-term regime, focusing to the investigation of key challenges of the long-term, in the main areas of bulk energy storage for long supply periods, use of surplus generation, full smart grid implementation and non-synchronous operation of power systems.

Table 2 Mid-Term Flexibility Roadmap Policy Checklist

Mid-Term Objectives	Mid-Term Policy Actions
Increase Market Incentives to Promote Greater Resource Participation for Flexibility	• Expand markets for flexibility—more flexibility service types, as well as more institutional participants, and technology sources (e.g., demand). • Reflect wholesale market prices at the retail level (develop appropriate tariffs where needed). • Remove barriers to vRES providing flexibility and grid support. • Allow negative wholesale market prices. • Remove any penalties that unduly restrict vRES participation in markets. • Implement peak demand contribution assessments for all resources on comparable bases (conventional generators, vRES, demand resources). • Modify vRES production incentives to encourage diverse deployment of resources. • Implement policies to encourage the retirement of baseload plants
Allow Demand-Side Market Participation	• Develop institutions and/or incentives to promote development and aggregation of demand management. • Comprehensive incentives and institutions to develop distributed generation resources.
Manage Distribution Grids	• Transition of distributed generation to require communication and control equipment for system dispatch. • Implement market design that allows the aggregation and optimization of distributed generation and demand management—the smart grid.

Mid-Term Objectives	Mid-Term Policy Actions
Enhance Transmission Network Functions	• Expand transmission system • Implement dynamic measurement, capability assessment, and control of transmission systems. • Institute geographic granularity of (nodal) market prices capable of reflecting price implications of relevant congestion points.
Increase Market Functionality	• Liberalize flexibility markets to allow bids for shorter time periods (e.g., hours or minutes instead of years) and for more specific purposes (e.g., generation increases separate from generation decreases). • Implement shorter gate closure times (no more than one hour). • Implement shorter trading/dispatch periods (no more than ten minutes). • Consolidate balancing areas explicitly or virtually through other mechanisms (e.g., imbalance markets) to cover the largest practicable regions. • Implement capacity markets for resources that are needed for reliability but for which existing market incentives are inadequate.
Lay Foundations to Address Long-Term Challenges	• Begin retirement of inflexible baseload resources. • Begin implementing new business paradigms and regulation for utilities (e.g., return on total system costs, decoupling, others). • Implement grid codes capable of operating power systems without synchronous generation. • Implement best practices for vRES forecasting and use of forecasts in planning and operations. • Implement vRES ramp forecasts and incorporate into dynamic reserve assessments. • Implement system-based energy storage valuation methods, and institute mechanisms (e.g., capacity payments, or minimum acquisition levels) to develop cost-effective energy • RD&D funding on investigation of key Long-Term challenges

4.3 Long-Term

Long-term phase policies are needed to pave the way for completing the power system transformation, facilitating the infrastructure changes needed to make a cost effective and reliable power system that relies primarily on variable renewable generation.

4.3.1 Power Supply During Low Output Events

Policies need to be put into place providing adequate incentives to providing power when wind and sun are in low supply. These policies will look at energy storage in the broadest sense (see pages 25-27), promoting the most cost effective energy storage whether as dedicated power grid energy storage, storage on the demand side (e.g., thermal or electric vehicles), or as primary energy (e.g., using carbon-neutral fuels in conventional power plants).

4.3.2 Efficient Use of "Surplus" Generation

Policies are put into effect to ensure the maximum possible use of electric generation available during periods of abundant vRES generation. Such policies may include new tariffs allowing use of intermittent, low cost use of electric generation to displace other fuels, or storing manufactured goods for later consumption.

4.3.3 Full Smart Grid Implementation

Policies are in place to make the widest use of smart gird techniques for managing distribution resources and making the fullest use of existing transmission infrastructure.

4.3.4 Stable Operation with Non-Synchronous Generation

Stable system operation with non-synchronous generation needs to be fully implemented. Policies are in place to ensure grid codes at all levels (generation, transmission, and distribution) are capable of needed communication and control protocols for safe and reliable power system operations.

Table 3 Long-Term Flexibility Roadmap Policy Checklist

Long-Term Objectives	Long-Term Policy Actions
Able to Supply Power during Low Output Events	• Implement incentives to ensure adequate resources under for low output events.
Efficient Use of Power During High Output Events	• Complete phase out of inflexible baseload resources. Implement policies develop optional uses of electric power (e.g., thermal energy storage requirements, dual fuel boiler capability, etc.).
Full Smart Grid Implementation	• Maximize use of transmission grid infrastructure and distributed generation and end-use flexibility options.
Ensure Stable Operation with Non-Synchronous Generation	• Require all vRES (above a certain size and/or vintage) to be capable of providing needed ancillary services through markets and grid codes.

5 Roadmap Summary

Achieving the vision will require a significant transformation of today's power systems. There is a wide range of actions to transform the power systems of today that need to be implemented, broadly illustrated in Figure 5 and described in more detail below. Not all of the changes are needed immediately. There is a progression of actions that will be most economically implemented if taken in coordination with the increasing reliance on vRES. The transformation will be unique to each system, but may be broadly divided into three development periods:

- Near-term up to about 10% of energy coming from vRES.
- Mid-term for penetration levels in the range of 50%.
- Long-term for the highest penetration levels—approaching 100%.

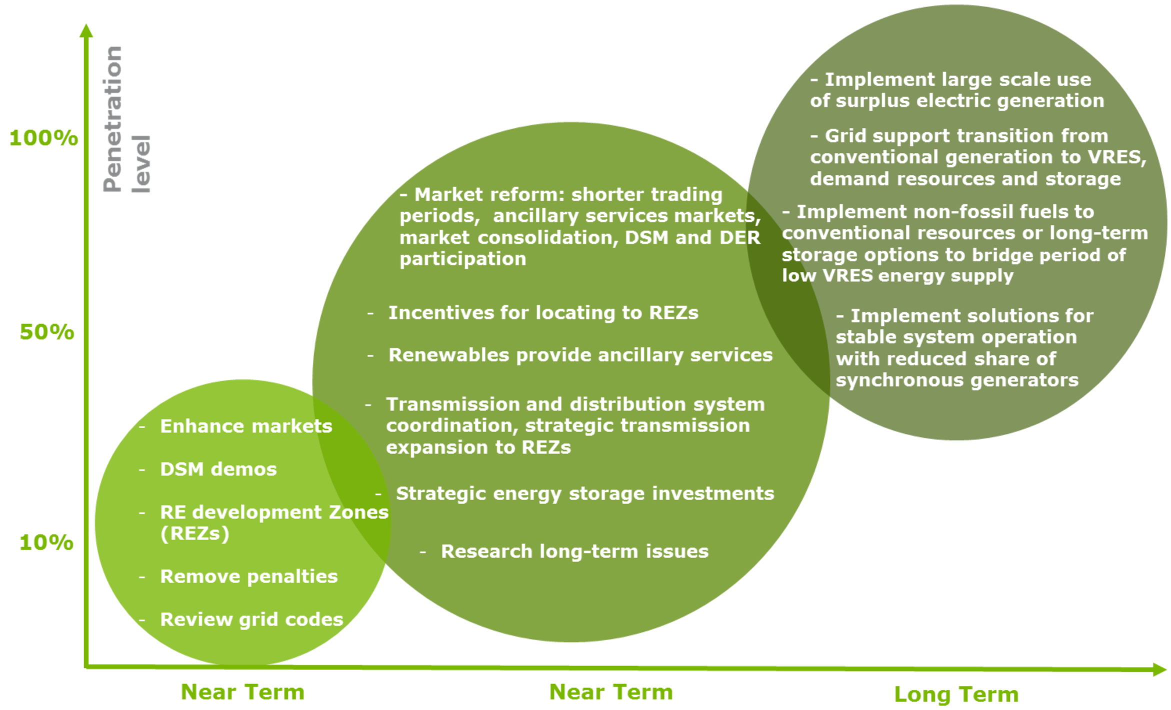

Figure 5 Changes needed for the transformation of the power system with growing vRES penetration levels.

These periods are not entirely distinct generalizations of the transformation process. They are merely guides to what is coming, and suggestive of measures to consider for systems along the development path. Given the growing concern over carbon emissions, it would be a mistake to assume that today's penetration level is the end point for any system that falls short of climate targets.

5.1 Near-Term

Transforming the planning and operation of today's power system will take place over time. Baseload units will be phased out in favour of more flexible generation. Energy storage will become increasingly important as the value of flexibility increases and the wholesale price of energy drops in response to low variable cost renewable resources. It will not be cost effective to transform the system over night. Even with new renewable resources beating the cost of new conventional generation, the sunk costs in conventional generation make exchanging old plants for new ones an expensive proposition. Nevertheless, some actions are needed in the near-term to reduce the cost of integrating vRES and to lay the foundation for higher penetration levels to follow.

Prudent near-term activities allow the efficient incorporation of variable generation at relatively modest levels, with relatively modest changes to power system markets and operations. Changes at the distribution level will be needed in systems where the vRES primarily interconnect at that level. Consideration of future-proof grid codes should be undertaken at an early stage to ensure a minimum of future retrofitting. The near-term is an appropriate time to envision the creation of renewable energy development zones or other market measures to encourage appropriate development of diverse vRES that can reduce future integration costs.

5.2 Mid-Term

The most wide-ranging changes are found in the broad mid-term period. Change will be driven by increasingly higher value placed on power system flexibility and the realization that making most efficient use of existing flexibility sources is far less expensive than dedicated solutions involving large infrastructure investments.

Substantial market reforms to allow broader participation in supplying both power and grid support services need to occur here. Markets need to be geographically expanded and punitive penalties that have out-sized negative impacts to vRES need to be adjusted. Market trading and grid operating periods are shortened to allow more accurate scheduling of variable generation, and allow flexibility contributions from more market participants.

Grid codes and interconnection requirements are restructured to accommodate larger penetration of variable generation into the future. Greater participation from demand resources and distributed generation and storage opportunities need to be developed and promoted. Smart grid solutions to communicating and controlling equipment at all levels from distribution grid to high voltage transmission need to be developed and demonstrated. Institutions to aggregate distribution system resources and to operate the smart grid may need to be developed. Energy storage needs to be encouraged where it can provide net benefit.

5.3 Long-Term

As variable generation becomes the dominant provider of energy, markets will focus almost entirely on optionality and flexibility. Conventional baseload generation will be retired and Smart grid solutions will make optimal use of available flexibility in transmission and distribution system components.

Times of energy abundance will increase in frequency and facilitate carbon-free electric power to begin powering other sectors, especially transportation and industrial process heating. Variable resources and energy storage will be able to provide all grid support services necessary to the reliable and stable operation of the power system.

Energy storage becomes an important priority and significant provider of energy when renewable energy is unavailable. Sources of energy storage may include conventional resources relying on unconventional fuels stored in conventional infrastructure.

5.4 Conclusion

Building sufficient flexibility into power systems that rely primarily on power from variable energy resources involves a transformation in roughly three phases corresponding to levels of variable resource development. Lower penetration levels up to about 10% are identified with a near-term phase as most systems have not yet reached those levels. The mid-term identifies systems with renewable energy supplying up to the mid double digits. The longer-term phase is associated with vRES contributing most or all power needs.

Both near-term and mid-term challenges associated with integrating variable renewable generation are largely creating the institutional framework necessary to driving the technological transformation. They focus primarily on accessing untapped flexibility in existing infrastructure and improving efficiency of electric markets to correctly reflect the value of flexibility and reaching out to greater participation— including end use loads. The biggest institutional and policy changes are needed in the mid-term to access the lowest cost flexibility inherent in existing power system infrastructure.

Relying almost entirely on variable renewable generation requires grid support services fully transitioning away from fossil generators to other sources, including: the renewable generators themselves, end use sources, and energy storage. An economic requirement will be ensuring the highest value use of occasional large power surpluses when high levels of renewable generation coincide with low levels of demand. Finally, the central issue is ensuring reliable and continuous service during periods of low renewable energy production that can last several weeks. This final challenge may be addressed through technological improvement in energy storage, or in relying on renewable energy-sourced fuels for conventional generation.

Although the technical issues appear manageable, managing the institutional changes around the transformation is likely to be the most daunting part of the transformation.

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