Status Report on Power System Transformation

A 21st Century Power Partnership Report

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7. Joint Institute for Strategic Energy Analysis

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CLEAN ENERGY MINISTERIAL
Accelerating the Transition to Clean Energy Technologies

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Preface

Power systems are among the largest and most complex systems ever created by humans. Transforming them will be a correspondingly complex process. As chronicled in previous reports from the 21st Century Power Partnership, power system transformation has multiple drivers—for example technological advances, policy goals, and social change—and multiple enablers, especially policy, financial, and technical innovation.

Perhaps one of the most significant trends in power system transformation is the growing democratization and diversification of supply. Enabled by technological, policy, and business model innovations, power systems are moving from being purely centralized systems to a more complex and interacting set of systems at multiple levels. In particular, transformation entails more decentralized assets, where consumers gain more ability to choose, and where distributed solutions are an integral part of the electricity system.

These innovations are fueling the growth of energy entrepreneurship, disrupting traditional energy business models and enabling new models for achieving secure, affordable, and clean power systems. In turn, this evolution has implications for the regulatory compact, in which regulated monopolies are increasingly subjected to competition not only to promote cost reductions, but also to introduce more innovation, improved reliability, and greater environmental sustainability.

There are many reports and materials available that chart the ways and means towards power sector transformation. Many of these are prescriptive or forward looking. Yet we still lack an overall picture of what power sector transformation actually represents, what forms of it have been happening around the world today, and what the status of this transformation is globally. This report aims to address this need, and is intended to provide an evidence-based picture that can evolve and be updated and re-issued in the years ahead. The picture is complex, but we have tried to capture its essential elements.

The report does not provide statistics, although it does consider some possible quantitative indicators that could be refined in the future. Rather, this report aims to bolster the evidence base for power system transformation by providing a collection of empirical examples of the types of innovations that are emerging around the world. This collection of examples can serve as a unique source of real-world evidence—and inspiration—for showing what power sector transformation is and how it is being achieved today. As the cases reveal, the word "innovation" itself is not limited to merely technology, but applies widely across policy, planning, operation, finance, and business models.

Much learning is possible from the collection of examples pointed to in this report. But this is only a first step. Importantly, power system transformation is an *active process.* Subsequent editions of this report will update the map of innovation and diffusion making it easier to track and learn from transformation, thereby supporting the goals of the Clean Energy Ministerial (CEM) to accelerate the realization of clean, reliable, and affordable energy systems.

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Executive Summary

This report has three primary goals: (1) to articulate the concept of power system transformation; (2) to explore the current global landscape of 'innovations' that constitute power system transformation and provide evidence of how these innovations are emerging; and (3) to suggest an analytical framework for assessing the status of power system transformation on an on-going basis.

Power system transformation is a complex, active process that is taking place at different rates and in different forms around the world. This transformation has multiple drivers, including technological advances, policy goals, and social change, and multiple enablers, especially policy, financial, and business model innovation. In response to evolving policies and customer preferences, investment patterns are changing rapidly and will continue to change over the coming decades. Investment is flowing increasingly not just toward new generation technologies like renewable energy and cleaner conventional generation, but toward an ecosystem of smarter grids, energy efficiency technologies, demand-side flexibility, storage, electric vehicles and integrated heating and cooling systems. Many of these elements can be seen individually across the world today, yet a clear picture of the breadth and depth of power system transformation is still limited.

This report aims to bring that picture into sharper focus, bolstering the evidence base for power system transformation by providing a collection of empirical examples of the types of innovations that are emerging around the world. This collection of examples can serve as a unique source of real-world evidence—and inspiration—to enable decision makers to take action. As the cases reveal, the word "innovation" itself is not limited to merely technology, but applies widely across market design, planning, operation, institutional coordination, finance, business models, and stakeholder engagement.

Innovations in power system transformation can be seen in eleven domains. In each of these eleven domains, this report describes specific types of innovations that are clearly emerging, and also provides empirical examples and evidence for each of those innovations from around the world. This picture of power system transformation as an ecosystem of interrelated innovation domains, substantiated by empirical examples, is a unique and pioneering method to capture the status of power system transformation, as well as to inform policy-making on the possible range of goals and desired outcomes.

The eleven innovation domains in this ecosystem include:

1. **Environmental Stewardship**. With increasing attention to climate change, urban air quality, water scarcity, and other environmental challenges, as well as significant decreases in the costs of some low-carbon technologies, robust electricity planning now integrates a broader set of evaluation criteria when considering power sector options. Planning processes and policies are increasingly introduced to achieve emission reduction targets, reduce water use, and meet environmental standards and regulations. Innovations from

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governments, regulators, utilities, and power producers are helping to transform traditional electricity planning and deploy innovative technologies and approaches to meet environmental goals.

2. **Transmission Systems**. Transmission system innovation is emerging in both planning and operational spheres. The addition of wind and solar has reinforced the value of larger balancing areas, not only because load diversity and generation reserves can help to balance larger amounts of variable generation, but also because the aggregate variability of these renewable energy sources declines as the balancing areas grow larger. Coordinated efforts for transmission planning that cut across balancing areas or national borders can enable better use of existing generation and transmission resources and can also inform efficient opportunities for developing new transmission lines. Innovative methods of operating transmission systems, such as data rich "smart transmission" infrastructure, can also extract more value from investments in variable renewable energy.

3. **Distribution Systems**. Distribution system innovation is unlocking the potential for distribution networks to become self-optimizing, with their own balancing of variable generation and control over dynamic and flexible loads. The distribution system must increasingly manage two-way power flows from distributed generation and storage, and must engage in new forms of interaction and control both at the distribution system operator (DSO) level and with the bulk power system at the transmission system operator (TSO) level. DSOs will increasingly find value in monitoring, collecting, analyzing, and using data in new ways, and will analytically model their distribution systems to a degree far beyond current practice.

4. **Transmission-Distribution System Interface**. With the accelerating proliferation of a variety of distributed energy resources, the transmission-distribution boundary will become less physically distinct, but more important as a juncture of economic value, and a more prominent focus for innovation and public policy debate. Innovations are emerging that begin to address new market, regulatory, and technical control structures to manage and define this evolving boundary.

5. **Finance, Markets, Pricing, and Cost Allocation**. Financial flows are a linchpin of power system functioning. Markets, pricing, and cost allocation are evolving in response to, and in support of, power system transformation. Four dominant modes of innovation emerge: new ways of bringing finance into overall power-sector investment; new ways of directing that finance to priority areas; new pricing mechanisms and dynamics coupled with "smart" technologies to unlock new system and end-user behaviors, and new market mechanisms to also unlock new system efficiencies and improve system flexibility.

6. **Static and Dynamic Load**. Energy efficiency (static load) and intelligent demand (dynamic load) are both becoming more cost-effective to deploy and manage. A variety of technologies are unlocking the innovations necessary to make loads more efficient and dynamic. These innovations link end-use consumers with

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various aspects of grid services and operation. Widespread deployment of smart meters and other enabling technologies can facilitate new pricing models, new patterns of demand and customer behavior, and new sources of load flexibility. This means that load can be adjusted in magnitude, or time-shifted to other periods in response to a variety of system conditions, opening significant new pathways for power system planning, operation, and investment.

7. **Flexible Generation**. The value of power system flexibility is growing dramatically, transforming the sources of flexibility. Thermal plants such as coal, combined cycle natural gas, and even nuclear, are being designed and retrofitted to provide system flexibility. Variable wind and solar plants are increasingly being outfitted with active power controls to provide flexibility and grid services. In addition, emerging changes to wholesale power market designs in many jurisdictions now allow variable renewable generation and responsive demand to bid into markets, and to be dispatched similarly to conventional plants.
8. **Integration with Heating and Cooling**. Innovations at the interface between electricity and thermal systems can unlock system benefits. Combined heat-and-power plants have historically been one of the main points of intersection between these systems, and will continue to provide greater levels of flexibility as they will remain key elements of transformed power systems. As network intelligence capabilities grow, many innovations are emerging to use distributed heating and cooling loads plus thermal storage in new ways to increase system efficiency and flexibility.
9. **Integration with Transport**. Two formerly separate sectors, power and transport are becoming increasingly connected through expanded deployment of hybrid and electric vehicles, and potentially also hydrogen fuel cell vehicles. Integrated transport and power infrastructure planning is supporting expansion of intelligent, data-driven systems that support flexibility, load balancing, and greater overall efficiency. The interface between these two sectors is becoming a key pillar of "smart city" planning that integrates electricity and transport systems.
10. **Energy Storage**. A fundament tenet of power systems—that supply must always equal (and follow) demand—is being replaced by more dynamic relationships between supply and demand. Enabled by innovations in energy storage and demand-side flexibility, power systems are becoming more flexible and better equipped to integrate additional variable generation, particularly wind and solar energy. Also, storage at the transmission, distribution, and end-user levels is beginning to provide clear economic and reliability value to transmission and distribution utilities and end-users, particularly with new innovations in business models.
11. **Microgrids**. Selectively autonomous power systems—microgrids—that can operate either stand-alone or connected to the bulk grid are becoming more commonplace and viable. The growth of microgrids is due to rapid technology cost declines, power system pricing models that allow microgrids to better capture the benefits of distributed resources (including integration of heating and cooling), and the emergence of new retail pricing policy frameworks and business

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models that can turn microgrids into profitable energy service providers, not just technology solutions.

Together, innovations across these 11 domains are unlocking new pathways to accelerated power system transformation. The growing momentum and real-world approaches to implementing these innovations in recent years is illustrated in this report by giving specific examples and evidence of each innovation across all 11 categories (see Chapter 2).

A Framework of Indicators

This report also suggests a framework of indicators for assessing the 'status' of power system transformation on an on-going basis, grouped into five categories. Within each category, a list of specific innovations from this report is suggested as a way to capturing progress and status (see Chapter 3).

A. **Wholesale Market Design and Bulk Power Grid Operation**. To what degree are wholesale design elements effectively applied in the power system to incentivize desired characteristics and behavior? To what degree are transmission grid operational strategies being effectively employed in the power system?

B. **Retail Markets and Distribution System & Demand Side Operations**. To what degree are retail market designs effectively applied in the power system to incentivize desired behavior? To what degree are distribution-level and/or demand-side operational strategies being effectively employed to manage distribution networks?

C. **Planning**. To what degree do planning frameworks account for the variety and interplay of power system trends? Do planning frameworks anticipate interplay between bulk-system, distributed, and demand-side resources that will exist in the future? Do planning frameworks adequately address both reliability and flexibility? Do planning frameworks explicitly account for resource conservation and emissions reductions?

D. **Technology**. To what degree are smart grid technologies being deployed and serving as the foundation for the innovations discussed in this report? To what degree are new highly flexible technologies—such as demand response, storage, fast-ramping conventional generators, and controllable variable renewable energy generators—being adopted within power systems? To what degree are new resource-saving and emissions-reducing technologies being adopted within power systems?

E. **Cross-Sectoral Integration**. To what degree are electric vehicles (both via charging and dynamic contributions to grid flexibility) explicitly included in market designs, planning frameworks, and operations? To what degree are heating and cooling loads and thermal storage mediums being incorporated within power system markets, planning, and operations?

This indicator framework can be useful as a navigational tool for decision makers in the complex process of transformation, and the framework will evolve over time as the dialogue around power system transformation grows.

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Key Messages for Decision Makers

From this report, five key messages emerge for decision makers:

- Evidence from around the world highlights that power system transformation is already happening and is accelerating.
- Power system transformation can help to achieve the public policy goal of clean, affordable, and reliable power systems.
- Power system transformation is fueled by various distinct forces, each powerful in its own right, including technology cost reductions, responses to climate change and local pollution, convergence with information technologies, changing customer preferences, and national fiscal and energy security strategies.
- Innovations in power system transformation are not easily captured by typical technology-centric definitions of "innovation." Important innovations are also happening in business models and entrepreneurship, policy making, planning processes, operational practices, finance, regulation, and stakeholder engagement.
- While power system transformation cannot be measured as directly or easily as investment flows or gigawatts of capacity, it can be measured, and therefore tracked, to assist in evaluation of policy and regulatory efficacy.

This first edition is a preliminary effort to initiate a more global dialogue about the subject of power system transformation. Subsequent editions of this report will continue to update the map of innovation and diffusion, making it easier to track and learn from transformation, and to refine the measurement of the effectiveness of various innovations. Such an evolving picture of the global landscape of transformation innovation can strongly support the goals of the CEM in accelerating achievement of clean energy systems. Suggestions for further innovations, concrete examples, and approaches to tracking status and effective practices are welcomed from readers.

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Acronyms

10YNDP	Ten-Year Network Development Plan (Europe)
ADR	automated demand response
ASEAN	Association of Southeast Asian Nations
BPA	Bonneville Power Administration (Oregon, United States)
CAISO	California Independent System Operator (United States)
CAREC	Central Asia Regional Economic Cooperation
CEM	Clean Energy Ministerial
CER	Commission for Energy Regulation (Ireland)
CHP	combined heat and power
CII	Confederation of Indian Industry
CRE	Comisión Reguladora de Energía (Mexico)
CREZ	Competitive Renewable Energy Zones (Texas, United States)
CSP	concentrating solar power
CVR	conservation voltage reduction
DEP	delivered energy productivity
DER	distributed energy resources
DFIG	double-fed induction generator
DG	distributed generation
DGIP	Distributed Generation Interconnection Plan (Hawaii, United States)
DLR	dynamic line rating
DR	demand response
DSO	distribution system operator
DSP	distributed system platform
ECOWAS	Economic Community of West African States
EIM	energy imbalance market
ENTSO-E	European Network of Transmission System Operators for Electricity
ERCOT	Electric Reliability Council of Texas (United States)
ERERA	ECOWAS Regional Electricity Regulatory Authority
EU	European Union
FERC	Federal Energy Regulatory Commission (United States)
GIVAR	Grid Integration of Variable Renewables
GoK	Government of Korea
GPMDG	Green Power Market Development Group (India)
GW	gigawatt
GWh	gigawatt-hour
HECO	Hawaiian Electric Companies (United States)
IEA	International Energy Agency
IEPR	Integrated Energy Policy Report (California, United States)
IPC	Idaho Power Company (United States)
IRP	integrated resource plan

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ISO	Independent System Operator
kWh	kilowatt-hour
MRC	Mekong River Commission (Asia)
NAMA	Nationally Appropriate Mitigation Action
NCCAP	National Climate Change Action Plan (Kenya)
NEM	National Electricity Market (Australia)
NEMMP	National Electric Mobility Mission Plan (India)
NYISO	New York (United States) Independent System Operator
NYPA	New York (United States) Power Authority
PECC	Special Program on Climate Change (Mexico)
PMU	Phasor Measurement Units
PUCT	Public Utility Commission of Texas (United States)
PV	photovoltaics
PWEP	Plan-it Wise Energy Program (Connecticut, United States)
RISE	Readiness for Investment in Sustainable Energy
RIT	Renewables Integration Tool
SCE	Southern California Edison (United States)
SDG&E	San Diego Gas & Electric (California, United States)
SENER	Secretaría de Energía de México
SPIDERS	Smart Power Infrastructure Demonstration for Energy Reliability (United States)
SPP	Statewide Pricing Pilot (California, United States)
T-D	transmission-distribution (boundary)
TSO	transmission system operator
VPP	virtual power plant
WAPP	West Africa Power Pool
WRI	World Resources Institute (India)

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1 Introduction to Power System Transformation

Toward a Definition of Power System Transformation

To achieve sustainable, reliable, resilient, and accessible energy, the scale of required power system investment is vast, necessitating dramatic increases in deployment of clean energy generation and grid infrastructure., The International Energy Agency (IEA) estimates $17–$19 trillion of cumulative power system investment (including both grids and power plants) will be required through 2035 under the "New Policies" and "450" scenarios. The IEA also estimates a need for an additional $8–$13 trillion of investment in energy efficiency over this period, with the more aggressive "450" Scenario resulting in significant reductions in total investment in fossil fuels (see Figure 1).

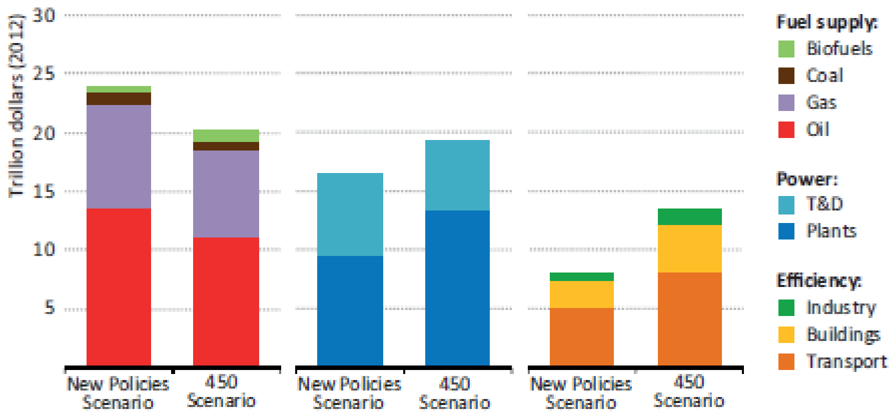

Figure 1. World cumulative investment in energy supply and energy efficiency, 2014–2035, in the "New Policies" and "450" Scenario[1]

Various pathways are possible to achieve both sustainable power systems and universal energy access. Broadly speaking, all sustainable energy pathways will require significant changes from "business as usual," and all will rely upon accelerating investment in renewable energy, energy efficiency, and a broad range of other sustainable energy technologies. Pathways will vary by jurisdiction, and will have different implications for the nature of power system evolution. Globally, policy and regulation have increasingly begun to focus on how to incentivize investments in sustainable energy resources and the complementary systems that maximize their value.

The capital cost of renewable energy technologies has typically been the main constraint on their deployment. Accordingly, policy attention has largely focused on reducing those price differentials. Notably, however, the cost barriers to widespread renewable energy deployment are falling, and generally speaking, the more renewable energy technologies are deployed, the more capital costs are likely to fall. This means that, increasingly, *system-level integration* considerations represent one of the main barriers in the transition to power systems that rely on high shares of renewable energy, rather than technology costs. Accordingly, in jurisdictions where renewable energy is expected to be a major pillar of future power systems, policy and regulatory attention is shifting to the new

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planning processes and complementary innovations that will maximize value and integration.

In addition to renewable energy, many other factors are driving or facilitating system-level transformation. For example, smart grid deployments will be driven by increased demands for customer engagement and reliability. New business and finance models are unlocking new sources of investment, and changing the nature of the electric power industry itself. Energy storage, intelligent heating and cooling, electric vehicles, and a variety of demand-side innovations all offer tangible value streams and will have new roles to play. Different combinations of these innovations, tailored to each national and regional context, will give rise to transformed power systems around the world.

Power system transformation is an *active, ongoing process*, not an end-goal. In response to policies and customer preferences, investment patterns are changing now and will continue to change over the coming decades, flowing increasingly not just toward new generation technologies, but toward smarter grids, energy efficiency technologies, demand-side flexibility, storage, and system assets not yet invented or imagined. The growing ubiquity of intelligent networks and innovation in power system business models will add an element of dynamism to the entire process.

In this light, a preliminary definition of power system transformation might be: **the active process of creating the policy environments that promote investment in—and innovation towards—secure, smart, affordable, clean, and reliable power systems.**

Refining the Definition: Measuring the Power System Transformation

Several observations can add depth to this preliminary definition. First, effective actions will successfully increase the speed and scale of investment in power system assets. Attention to investment impacts is crucial given the scale of investment required for the dual goals of global energy access and low-carbon power systems.[2]

Second, effective actions will facilitate increases in "delivered energy productivity" or DEP. DEP can be understood as the product of two related factors:

1) *Raising the economic output of every kilowatt-hour (kWh) generated,*

   - and -

2) *Reducing the pollution of every kWh generated.*

These factors are familiar from climate, energy, and public health policy, and are sometimes referred to as 'energy intensity of economic activity' and 'emissions intensity of energy,' respectively. Specific, targeted actions can in combination achieve greater delivered energy productivity. With regard to the first factor, energy productivity gains can be achieved through measures to promote intelligent energy efficiency across industrial, commercial, and residential sectors. Reduced energy intensity allows for a continued decoupling of economic output from energy usage.

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The second factor requires harnessing maximum value from clean energy sources. As zero- and low-carbon generation grows, and as supply becomes more distributed, it will become more important to guide system evolution in a way that makes the most of clean energy sources. These system-level measures, such as increasing system flexibility and grid intelligence, and promoting integration with other energy sectors like transport and thermal systems, require new modes of planning and operating power systems. Successfully implemented, they increase the economic and environmental returns on investments in supply, and increase the value and quality of service to customers.

System intelligence emerges as a common element that will enable gains in both energy productivity and energy delivery from zero- and low-carbon sources. System intelligence also adds fuel for innovation and investment, as entrepreneurs can cross-pollinate between the information technology and power sectors.

Together, the two factors of *delivered energy productivity,* enabled by system intelligence, form the rationale for the pillars of CEM activities: clean supply, grid integration and smart grids, and energy efficiency. The 21st Century Power Partnership, one of the initiatives of the CEM, aims to provide holistic insights across these domains.

These observations also lead to a refinement of the definition of power system transformation:

> **Power system transformation is the active process of creating the policy environments, and the planning and operating practices, which accelerate investment and innovation in power systems that maximize the use of sustainable energy and maximize delivered energy productivity, while also fostering the integration of power systems with transportation, heating and cooling, and broader resource management.**

This concept serves as the working definition that guides this report. The definition provides useful guidance to decision makers: actions should be targeted to increase impact on investment, on innovation, on delivered energy productivity, and on cross-sectoral system integration.

Bringing the Definition to Life: The Landscape and Status of Innovation

With this working definition in hand, this report turns to focus on establishing an evidence base for power system transformation—a collection of empirical examples of the types of innovations that are emerging around the world to enable sustainable energy pathways. The word "innovation" itself is not limited to merely technology, but applies to a wide range of improvements in policy, planning, operation, and business models, as well as fundamental reconceptualizations of the ways in which power systems have traditionally operated over much of the past century. Other authors have also started to use the word "innovation" in this broader context.[3]

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From this collection of innovation examples, a clearer picture of the contemporary status of power system transformation begins to take shape. In future editions of this report, the picture will be updated and further clarified. This detailed picture of innovations complements several important efforts to track the evolution of power system transformation undertaken by other organizations, such as the Sustainable Energy for All "Global Tracking Framework," and the World Bank "Readiness for Investment in Sustainable Energy" framework.[4]

Various features of the power system transformation landscape have been emerging incrementally over the past 10–25 years in many countries and regions as a result of a wide diversity of restructuring and reform efforts. While significant market and institutional restructuring took place in the 1990s and early 2000s (mainly in parts of the United States, Europe, Latin America, and Australia), and since then in other countries, these institutional and market reforms were predominantly focused on unbundling, privatization, economic efficiency, competition, and transparency. In many ways, while these efforts significantly re-ordered the ecosystem of actors, they did not *fundamentally* transform power systems, as citizens remained only as consumers of energy, and as energy and emissions intensities did not dramatically change.

Today, a broader constellation of factors is driving transformation efforts. Concerns over the local and global impacts of fossil fuel emissions are growing. Energy security relationships are evolving swiftly. The imperative of universal energy access is widely recognized. Costs are declining for variable renewables like solar and wind, for smart grid technologies, for energy storage, for energy efficiency, and for intelligent devices and demand management. Interactions with water and land-use sectors are becoming more acute and apparent. And in the background, dramatic advances in network intelligence and system optimization hold the potential for disruptive innovation.

Messages for Policymakers

This introduction has laid out a framework for the expected long-term directions and results of power sector transformation, culminating in the definition given above. As will become clear in the remainder of the report, five key messages emerge:

- Evidence from around the world highlights that power system transformation is already happening and is accelerating.
- Power system transformation can help to achieve the public policy goal of clean, affordable, and reliable power systems.
- Power system transformation is fueled by various distinct forces, each powerful in its own right, including technology cost reductions, responses to climate change and local pollution, convergence with information technologies, changing customer preferences, and national fiscal and energy security strategies.
- Innovations in power system transformation are not easily captured by typical technology-centric definitions of "innovation." Important innovations are also

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happening in business models and entrepreneurship, policy making, planning processes, operational practices, finance, regulation, and stakeholder engagement.

- While power system transformation cannot be measured as directly or easily as investment flows or gigawatts of capacity, it can indeed be measured, and therefore tracked, to assist in evaluation of policy and regulatory efficacy. This report suggests some new approaches to measurement and tracking that might complement existing tracking systems by other international agencies, further facilitating the discovery and adoption of best practices.

Report Organization

The report is organized as follows. Section 2 articulates a set of emerging innovations in planning, operations, technology, and other aspects of power systems under transformation. These innovations are grouped into 11 domains, and all reflect a departure from ways in which power systems have been planned and operated historically. For each innovation, Section 2 also provides a set of examples or evidence from emerging real-world experience and practice around the world. Section 2 thus allows policymakers to grasp the types of intermediate approaches that are needed along the way to power sector transformation, and many of the elements of what "transformation" actually means in practice today.

Section 3 then outlines some possible indicators for tracking progress towards power system transformation, and for determining where transformation stands today. These indicators can be useful to navigate the broader process of recognizing and harnessing the driving factors mentioned above toward desired visions of power system transformation.

Finally, Section 4 provides insight into the role of the regulator and the kinds of regulatory challenges and functions that are needed now and in the future to initiate and accelerate the innovations described in Section 2. From understanding the innovations presented in this paper, policymakers will be in a better position to enact clear frameworks that enable regulators to fulfill these needed functions.

Section 5 concludes with considerations for further international collaboration.

Managing power system transformation will become an increasingly important area of focus for regulators, system operators, policymakers, and citizens. We hope that this report and subsequent editions are useful to decision makers, both by establishing a useful framework for defining and measuring power system transformation, and also by illuminating real-world examples of innovation that can motivate and inspire proactive decision making.

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2 Innovations for Power System Transformation

This section articulates a series of emerging innovations for power system transformation around the world, and provides real-world examples and evidence of these innovations. The examples in this section, while diverse, all illuminate key areas of activity for accelerating investment in—and innovation towards—power systems that maximize sustainable energy and maximize delivered energy productivity.

To more easily portray the emerging landscape of power system transformation, the innovations and examples are divided into 11 domains. Many individual examples of innovation provide evidence of innovation in more than one domain, and are discussed multiple times in the report. Thus, the domains given here should be considered fluid. These 11 domains are:

1. Environmental Stewardship
2. Transmission System
3. Distribution System
4. Transmission-Distribution Boundary
5. Finance, Markets, Pricing and Cost Allocation
6. Static and Dynamic Load
7. Flexible Generation
8. Integration with Heating and Cooling
9. Integration with Transport
10. Energy Storage
11. Microgrids

Ideally, integrated approaches to power system transformation would encourage coordinated innovation in most if not all of these domains. As the importance of power system transformation grows, approaches that allow alignment and coordination of innovation across these domains will become correspondingly important.

2.1 Environmental Stewardship

In the past, power sector planning focused predominantly on providing reliable electricity at the least cost. While the least cost imperative was generally consistent with public policy provisions at the time, it has proven increasingly simplistic over time, especially as the health and environmental aspects of power systems have become better understood and quantified. In the past, environmental considerations simply were not acute enough, and sustainable energy options were considered too costly, to warrant mainstream consideration in power system planning.

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In transforming power systems, increasing attention is paid to climate change, urban air quality, water scarcity, and other environmental challenges. Enabled by significant decreases in the costs of sustainable energy technologies, robust electricity planning now integrates a broader set of evaluation criteria when considering power sector options. Planning processes and policies are increasingly introduced to achieve emission reduction targets, reduce water use, meet energy access policy goals, and meet environmental standards and regulations. Innovation from governments, regulators, utilities, and power producers is helping to transform traditional electricity planning and deploy innovative technologies and approaches to meet environmental goals.

Innovation #1: Integrated Resource and Low Emission Development Planning Approaches With Cross-Sectoral Linkages and Impacts

In various jurisdictions, innovative electricity sector strategic planning efforts are being adopted that move beyond basic, least-cost approaches to incorporate more robust analysis of complex cross-sectoral links, impacts, and tradeoffs. These strategic planning efforts provide a critical link between power sector transformation and broader environment and development goals, and are informing design of integrated policy portfolios. These planning efforts are also incorporating new models of stakeholder consultation and inclusion. Today, many national and subnational governments support integrated resource and/or low emission development planning efforts. Ultimately, these efforts are influencing national budget decisions and shifting a greater share of public and private investment to environmentally-sound technologies that accelerate renewable energy and energy efficiency solutions.

Examples and evidence

South Africa Department of Energy Integrated Resource Plan (IRP)

South Africa's IRP, approved in 2010, employs an inclusive and innovative approach to consider and "balance" multiple environmental and development priorities with least cost power sector planning. As with traditional electricity planning, a least cost optimization model was first used to develop various electricity supply scenarios. However, to build on these analytical efforts, a multi-criteria decision-making approach is now used to score and assess GHG emission, water use, regional development and various other qualitative and

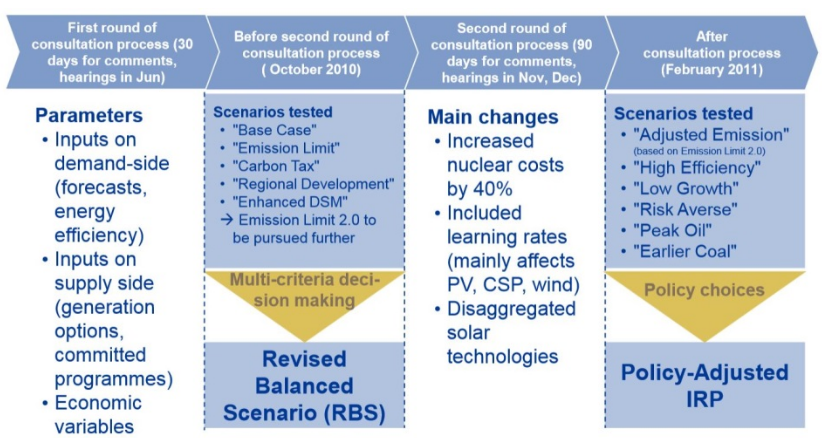

Figure 2. Illustration of South Africa IRP process

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quantitative impacts associated with the supply scenarios generated. South Africa's IRP approach also represents an expansion of stakeholder inclusivity. Under this approach, a cross-ministerial working group designed the multi-criteria assessment structure, noted in Figure 2, to consider power sector options. Over a 13-month period, various rounds of public stakeholder consultations were held to inform scenario assumptions and scoring and review iterations of the plan. Figure 2[5] illustrates the multiple rounds of stakeholder consultation, as well as the analytical process that led to the IRP. South Africa is currently updating the IRP to include revised assumptions and demand forecasts based on new data and information.[6]

Arizona (United States) Integrated Resource Plan

Breaking from traditional electricity planning approaches, Arizona Public Service (APS) utility's IRP emphasizes water and climate considerations, which are crucial in this arid region of the United States. Through an inclusive stakeholder approach in which landowners, electricity generators, customers, and others were actively engaged over a two year period, APS developed the 2012 IRP. The IRP assumes federal regulation of CO_2 within a fifteen year period, analyzes supply portfolios aligned with broader goals to diversify fuel and technology resources and support renewable energy and energy efficiency, and assesses emission costs and water consumption of various supply options. APS was one of the first utilities in the United States to consider water impacts of future electricity scenarios under the IRP.[7]

Bolivia, Ecuador, and Peru Multi-Sectoral Urban Planning

From 2012–2014, the Cities Footprint Project provided an early stage analytical foundation for innovative urban planning in La Paz, Bolivia, Quito, Ecuador, and Lima, Peru. Under this effort, various institutions[i] collaborated with municipal governments to estimate carbon and water footprints for the public, transport, commercial, industrial and residential sectors (see Figure 3[8]). These analyses informed development of action plans to reduce city-level water and energy footprints utilizing various renewable energy and energy efficiency technologies. In many cases the footprint assessments also informed local government policymaking and fed into broader stakeholder and private sector discussions and action. [9]

[i] Latin American Development Bank and the Climate and Development Knowledge Network, a team including Fundacion Futuro Latinoamericano, Servicios Ambientales S.A., and the Spanish network Carbonfeel.

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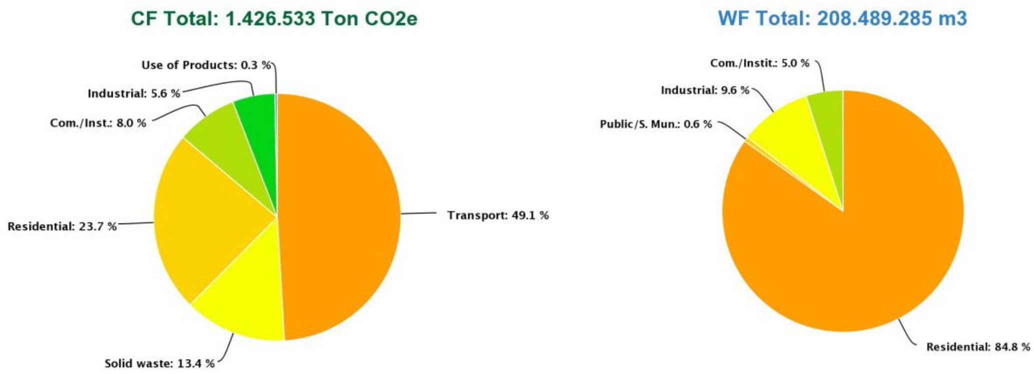

Figure 3. Multi-sectoral footprint results for La Paz, Bolivia

California (United States) Integrated Energy Policy Report (IEPR)

California's IEPR assesses energy sector trends and puts forth recommendations for policies and actions to ensure a reliable energy system while also supporting broader environmental, economic and social development goals. Updated every 2 years, the California Energy Commission leads an inclusive IEPR dialogue process that brings together national and local government, technical, private sector, and civil society stakeholders through workshops and consultations to discuss high level trends and recommendations for energy sector policies and programs. The most recent 2014 update to the IEPR focuses on transforming the transportation sector to meet critical environmental and energy goals including status and opportunities for electric vehicle and other low emission vehicle and infrastructure deployment. Along with other topics and updates, the 2014 IEPR also puts forth approaches to better integrate environmental concerns with renewable energy planning.

Greater Mekong River Delta Integrated Regional Planning

As water resources often traverse national boundaries, intergovernmental agreements are needed to support mutually beneficial outcomes. To support sustainable development in the Mekong River region, the Mekong River Commission (MRC) is an intergovernmental body that brings together the governments of Cambodia, Lao PDR, Thailand and Viet Nam.[10] As one activity, the MRC developed a Strategic Environmental Assessment in 2010 that evaluates complex linkages and interdependencies across water and electricity resources, and examines policy options, scenarios and related environmental, social and economic impacts.[11] The MRC also designed a Sustainable Hydropower Initiative that provides a framework for cooperation at the regional level to plan and manage hydro projects. The initiative developed common project guidelines and shared knowledge and good practices from across the participating countries, as well as other intergovernmental river basin organizations and international institutions.[12]

Kenya Integrated Climate-Energy Planning

Kenya's National Climate Change Action Plan (NCCAP), released in 2013, presents an approach to meet increasing power needs in a manner that reduces emissions and supports broader development goals. Based on analysis of low-carbon scenarios and prioritization of key actions under the NCCAP process, the Government of Kenya (GoK)

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submitted a large-scale geothermal development Nationally Appropriate Mitigation Action (NAMA) to the UN Framework Convention on Climate Change NAMA registry in 2014. GoK engaged a broad set of stakeholders over a 16 month period to inform development of the NAMA and ensure an inclusive and transparent approach. The NAMA focuses primarily on expanding private investment in geothermal development through design of risk mitigation and premium payment instruments supported by international technical assistance and capacity building.[13] By 2020, the NAMA could support expansion of approximately 1000 MW of geothermal capacity and reduce emissions by approximately 4.60 $MtCO_2$ per year.[14]

Mexico Integrated Climate-Energy Planning

Mexico's Special Program on Climate Change (PECC), developed through a stakeholder-led process and a partnership of 14 federal ministries, encompasses innovative power sector measures that support both climate and energy goals. Under the PECC launched in 2014, Mexico's Ministry of Energy (SENER) is establishing policies to support renewable energy grid integration and develop a Renewable Electricity Grid Integration Road Map to help meet an ambitious target of 35% renewable electricity by 2024. These activities are carried out with support from the 21st Century Power Partnership and the United States' Enhancing Capacity for Low Emission Development Strategies program, in close cooperation with Danish and German technical experts. In addition, SENER is working with the national grid operator, regulator, and utility to design a new national research and development (R&D) virtual center dedicated to grid integration research activities and peer learning activities. Mexico has taken a leading position to address climate change through transforming the country's power sector.

Innovation #2: Water-Saving Technology Deployment

Historically**,** power system planning did not take into account water consumption, or if it did, such accounting was only used to establish engineering limits for power plants, not to explicitly factor water as a system-wide resource. Thus, historical approaches have often failed to support sustainable water resource management. Today, leaders increasingly recognize the "energy-water nexus," and power needs are being met at reduced rates of water consumption.[15] As a result of integrated planning processes, and to address increasing water scarcity challenges, innovative thermal technologies are being deployed around the world, including:[16] dry cooling technologies that cool thermal steam using air rather than water, hybrid systems that combine wet and dry cooling,[ii] and technologies that use nontraditional water sources (e.g., brackish and waste water).[17]

[ii] Hybrid systems are typically used in settings with significant seasonal weather variations (e.g., greater use of dry cooling technology in cooler months).

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Examples and evidence

Dry Cooling for Concentrating Solar Thermal Power (CSP) in South Africa

To contribute to the country's broader goals to increase energy security and add 17,800 MW of renewable energy by 2030, South Africa is supporting development of CSP plants. Given water constraints, advanced dry cooling technologies are increasingly considered. Dry cooling reduces overall water consumption by CSP plants. Notably, Khi Solar One, developed by Abengoa Solar, is a 50 MW dry cooling CSP plant with two hours of thermal storage that uses innovative solar tower technology to increase plant efficiency through use of superheated steam. Khi Solar One is expected to reduce water consumption by two thirds as compared to traditional CSP plants, while also supporting CO_2 emission reduction.[18]

Dry Cooling for CSP in California

California is also a leader in deployment of dry cooling technology with the 392 MW nameplate capacity Ivanpah CSP plant that uses a closed-loop cycle system to convert steam back to water. Compared to traditional cooling technologies, water use is reduced by up to 95%.[19] Deployment of dry cooling technologies will continue to expand in California in the coming years, especially in the context of increasing water scarcity concerns. Other dry cooling CSP plants under construction in California include the 500-MW nameplate capacity Palen Solar Electric Generating System and the 150-MW nameplate capacity Rice Solar Energy Project. Each project is set to begin operations in 2016 and will utilize dry cooling power tower technology to significantly reduce water consumption.[20]

2.2 Transmission System

In the past, transmission network planning took into account customer load growth, generation growth, and overall reliability considerations. Planning was traditionally restricted to within established single-utility balancing areas. Modest changes to balancing areas and greater amounts of inter-regional planning have emerged over time from general moves toward wholesale market integration in some jurisdictions since the 1980s, which have reduced overall costs through the beneficial effects of load diversity and generation reserve sharing. But past efforts at balancing area changes and inter-regional planning have captured only a small part of the potential value of more integrated and flexible power systems. Also, historical transmission network planning did not require a significant focus on extending transmission to sites with high-quality variable renewable energy resources, which are often distant from load centers.

In transforming power systems, transmission system innovation is emerging in both planning and operation spheres. The addition of wind and solar has reinforced the value of larger balancing areas to provide geographic diversification to reduce supply variability. It is increasingly common for neighboring transmission system operators to work together to identify the best routes and processes for developing new transmission, determine how to fairly allocate transmission costs, and allow for competition among

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potential developers.[21] Increasing the size of balancing areas or integrating multiple balancing areas together can provide even more power system flexibility. Further, coordinated efforts for transmission planning that cut across balancing areas or even national borders can enable better use of existing generation and transmission resources and can also inform efficient opportunities for developing new transmission lines.[22] Innovative methods of operating transmission systems can also extract more value from investments in variable renewable energy, including data-rich “smart transmission” infrastructure.

This section highlights innovations in transmission planning and operation.

Innovation #1: Interregional and International Planning, and Balancing Area Expansion

Traditionally**,** transmission network planning was restricted to utility balancing areas. Over time, there has been a general move toward wholesale market integration in some parts of the world, which has continued with fits and starts since the 1980s, and which reduces overall costs through the beneficial effects of load diversity and generation reserve sharing. A typical result has been a growth in the geographical size of balancing areas alongside greater amounts of inter-regional planning. More recently, the addition of wind and solar has amplified the value of enlarging balancing areas, not only because load diversity and generation reserves can help to balance larger amounts of variable generation, but also because the overall variability of variable renewable energy declines as the balancing areas grow larger. In other words, there is a ‘geographic smoothing’ effect.

Today, neighboring transmission system operators are increasingly working together to identify the best routes and processes for developing new transmission, determine how to fairly allocate transmission costs, and allow for competition among potential developers. This is a key area of power system innovation.

Examples and evidence

EU-Wide Transmission Planning: “Ten-Year Network Development Plan”

The European Network of Transmission System Operators for Electricity (ENTSO-E) was established in 1999 in an effort to harmonize grid codes across Europe. Since 2010, one of the main activities of ENTSO-E is the Ten-Year Network Development Plan and Regional Investment Plan (10YNDP), a non-binding network planning report that informs continental energy planning. The 10YNDP is a biennial process that began in 2010 with the most recent final report released in December 2014.[23] The 10YNDP is fundamental in the move towards a fully integrated European energy market that will allow for more economical integration of renewable energy. The 2014 report included a longer time-horizon—out to 2030—and centers around four plausible pathways, reflecting possible variations in the speed of renewable energy uptake and national versus regional policy approaches to integrating renewables.[24]

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ASEAN Power Grid Initiative

The Association of Southeast Asian Nations (ASEAN) region intends to meet part of its rapidly growing demand with a 15% share of renewables in the power mix by 2015, building on to a 10% share reached in 2010.[iii,25] Additional demand will be met through energy savings, increased cross-border trade, and development of new generation sources, which are among the main focus areas of the 2007 Action Plan for Energy Cooperation 2010–2015.[26] Incorporated within the energy cooperation action plan is the ASEAN Power Grid initiative that aims to improve the security, reliability, and availability of energy throughout the region. Enhanced planning is exemplified by the transmission grid harmonization study developed in 2013 in conjunction with the Asian Development Bank that assessed national systems, recommended technical standards and guidelines for harmonizing integration; and prepared a plan for integration (see Figure 4).[27]

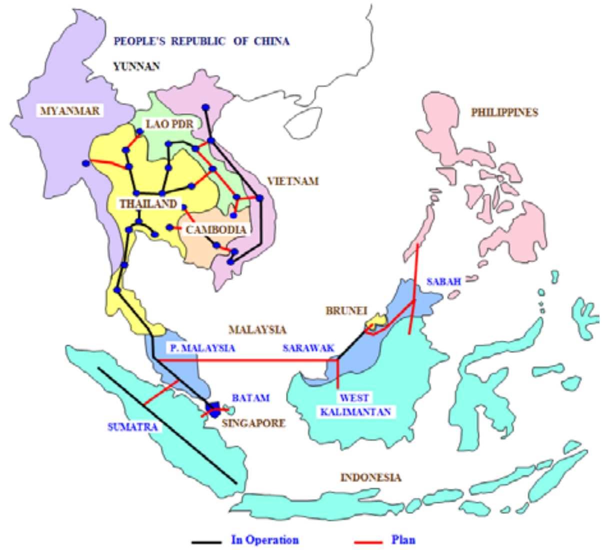

Figure 4. Illustration of the ASEAN Power Grid Initiative

Inter-Regional Planning in the United States: FERC Order 1000

In 2011, the U.S. Department of Energy's Federal Energy Regulatory Commission (FERC) issued Order 1000[28] requiring regional transmission planners to analyze alternative transmission investment options for new facilities and to develop a regional plan. The regional planning process must include public utility transmission providers and stakeholders and take into account state and federal regulations. Neighboring regional transmission planners are required to coordinate, share information on transmission needs, and identify whether there are interregional transmission facilities that could more effectively meet these needs.

Regional Integration and Planning in West Africa

The West Africa Power Pool (WAPP) was established in 1999 under the Economic Community of West African States (ECOWAS) with the objective of facilitating a reliable grid and common electricity market. WAPP has been undertaking a coordinated effort to meet an anticipated tripling of demand over the next decade via a portfolio of policies and programs to increase investments in power grid expansion, including the building of new interconnections (see Figure 5). Key to the regional power pool collaboration was the 2008 creation of the ECOWAS Regional Electricity Regulatory Authority (ERERA).[29] ERERA is in the process of developing harmonized operational

[iii] The statement does not specify which technologies are defined as renewable energy but they are assumed to be hydropower, geothermal, solar, wind, and biofuels.

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procedures and is increasingly focusing on issues of variable renewable energy integration and energy efficiency deployment.

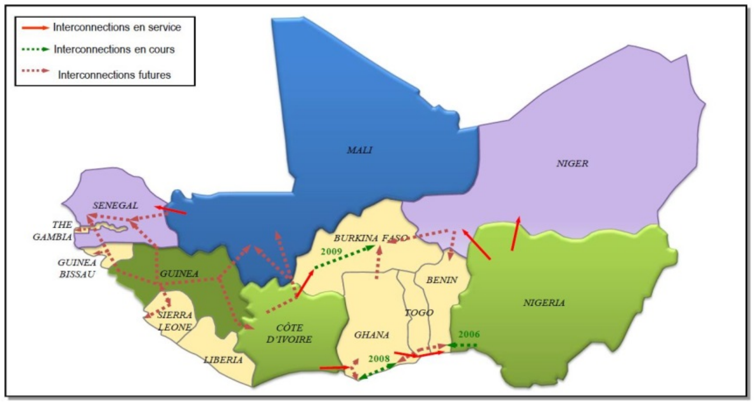

Figure 5. Illustration of Regional Grid Planning in West Africa

South Asia Transmission Integration and Interconnection

To increase overall system efficiency and reliability, the power systems of India, Bhutan and Nepal are now operating in interconnected synchronous mode. For example, a 500 MW HVDC interconnection between India and Bangladesh became operational in 2013, and is now heavily utilized.[30] Several additional inter-regional interconnections are under construction or being strengthened. In 2014, a South Asian Association for Regional Cooperation (SAARC) inter-governmental framework agreement was signed, promoting development of a common electricity market, and plans are to increase electricity exchanges between members of the SAARC common market.[31] Neighboring countries to India may also participate in India's electricity market with associated scheduling and accounting systems to be developed.[32]

Pentalateral Energy Forum Generation Adequacy Assessment

Generation adequacy refers to the capability of the power system to supply aggregate demand in all the steady states in which the power system may exist considering standard conditions. Traditionally, generation adequacy studies are performed within national borders. In 2015, a group of transmission system operators (TSOs) and research institutes from across central western Europe released a first-of-its-kind resource adequacy study that spanned the core Pentalateral Energy Forum members (France, Germany, Belgium, Netherlands, and Luxembourg) and also included Austria and Switzerland.[33] The study was also unique in harmonizing a shared data set of wind, solar, load, and generator data, and in modeling the system at a high resolution (hourly) across two select years (2016 and 2021). While wind and solar power are expected to grow significantly during the period, no resource adequacy issues linked to variable renewable energy were identified within the study horizon.

Innovation #2: Transmission Planning for Concentrated Areas of Renewable Energy

Historically, transmission network planning did not require a significant focus on extending transmission to sites with high-quality renewable energy resources, which are often distant from load centers. Today, more and more, transmission network planning explicitly forecasts and/or plans for expansions to specific renewable energy areas, analyzes how these areas will be served by the transmission network, and ultimately at

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times develops new transmission to serve these areas. However, there are several challenges involved in achieving least-cost network expansion to remote locations, including modifications to planning, the need for financing the lines, and mechanisms to engage stakeholders along the route of the lines. Several transmission operators and regulatory jurisdictions have created unique and innovative approaches to these issues.

Examples and evidence

Mexico 'Open Season' Planning

Due to transmission-related factors and remote locations, Mexican wind development was relatively slow in the early 2000s. The Mexico Ministry of Energy (SENER) and the national energy regulator (CRE) recognized the need for more transmission infrastructure to support wind development. However, historically CRE was restricted from allocating public funds for transmission improvements that were not for the public good and CRE could not coordinate planning and construction without firm commitments from generators for capacity payments. At the same time, developers could not secure financing without guaranteed transmission capacity. To address this stalemate, SENER and CRE developed a new planning process that could be invoked as often as needed. Termed "Open Season," the process identified transmission needs based on planned wind capacity and guaranteed that CRE would authorize this new infrastructure. The Open Season also serves to determine a least-cost transmission planning strategy and define a cost-sharing ratio for wind developers. This approach to planning enabled Mexico to access untapped wind resources and to lower investment costs for transmission developers (see Figure 6a and Figure 6b).[34]

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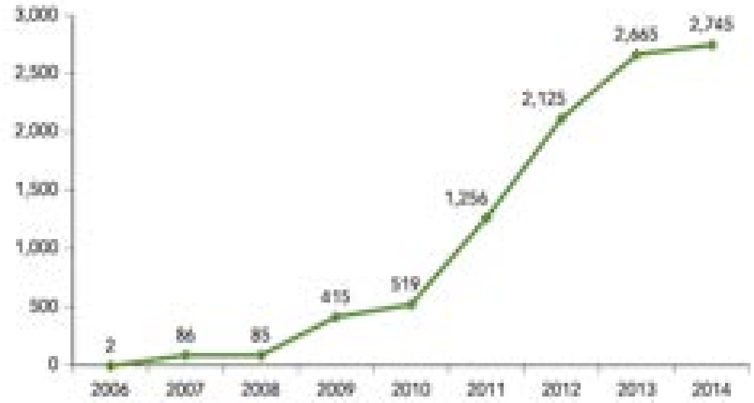

Note: All projects are committed or under construction.
Source: CFE 2010.

Figure 6a and 6b. La Ventosa wind power capacity growth and transmission planning

Texas "Competitive Renewable Energy Zones"

In 2005, the Texas legislature directed the Public Utility Commission of Texas (PUCT) to establish the Competitive Renewable Energy Zones (CREZ) process to coordinate expansion of transmission lines in areas with strong wind resources. The new legislation allowed the PUCT to facilitate development of transmission for CREZ without financial commitment from generators and with a guarantee to transmission developers that costs could be passed to ratepayers, even if lines were underutilized. From In 2014, the full CREZ project was completed, unlocking the cost-effective development of 18 GW of planned wind power capacity and reducing overall wind curtailment.

China Transmission Planning for Gigawatt-Scale Wind-Power "Bases"

China is planning a series of at least eight wind power "bases" in Gansu, Xinjiang, Inner Mongolia, Jilin, Hebei, Jiangsu, and Shandong provinces. These "bases" are specific wind development geographic areas with aggregate capacities of up to 10 GW for each base. As part of the planning for these bases, transmission planning will be undertaken in

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anticipation of the need to carry the power from these regions to distant population centers, particularly in the south of China. This is an example of coordinated long-term planning of both new wind capacity and the transmission required to serve those areas.[35]

Innovation #3: Including Transmission Considerations into Interconnection Application Processes

Traditionally, individual generator interconnections were handled separately from long-range transmission planning. As the emphasis on variable renewable energy has grown, these two planning processes are increasingly conducted in a coordinated fashion. Innovations in this area can reduce project costs and delays, thereby reducing project risk and increasing investor interest, and give system operators greater clarity on interactions between new and existing generation.

Examples and evidence

Ireland "Gate" Process

With applications for wind development growing rapidly, in 2004 Ireland developed a new approach for reviewing wind farm and conventional generation interconnection agreements by grouping applications into "Gates." The Ireland Commission for Energy Regulation (CER) developed a set of criteria to outline the next eligible batch of wind farms that could be processed and connected as a Gate. Subgroups of projects were determined within each Gate based on project locations and interactions.[36] The third Gate was completed in 2011 and, taken together, all three Gates supported 5,673 MW of new wind development and 2,000 MW of conventional generation.

Innovation #4: Integrating Forecasting Into Transmission Operations

Forecasts of load and variable renewable energy production become more accurate closer to dispatch. System operators can use advanced forecasts for scheduling purposes, but then regularly update forecasts as dispatch approaches. Innovations in this domain can significantly reduce variable renewable energy curtailment and can avoid overestimating the amount of reserves needed for grid balancing.

Examples and evidence

Idaho Power Company (United States) Renewable Integration Tools

The Idaho Power Company (IPC), which supplies power to Idaho and Oregon, has developed a new Renewables Integration Tool (RIT) to support operators in cost-effective dispatch of wind generation. The RIT consists of several models and databases for forecasting weather conditions and wind resources that can be quickly integrated into operations. RIT has demonstrated a 26% to 32% improvement in forecasting accuracy with costs savings estimated to be around $287,000. IPC is looking to improve weather data to further leverage cost efficiencies of applying RIT to operational practices.

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Germany Wind and Solar Forecasting

German transmission system operators commonly incorporate advanced forecasting into scheduling and dispatch.[37] Multiple forecasts are considered by system operators as an 'ensemble,' increasing the accuracy of the system under particular weather situations, and generally enhancing the level of certainty of renewable energy production.

Wind Forecasting in the Australian National Electricity Market

The Australian National Electricity Market (NEM) has developed, with significant stakeholder input, a wind forecast system that is fully integrated into the market dispatch and pricing process (Cochran *et al.* 2012). The centrally controlled system incorporates a large number of data inputs including individual wind farm outputs, ground-based weather stations, and satellite imagery.

Innovation #5: Transmission Operation with Real Time System Intelligence

Traditionally, due to cost and complexity, real time system intelligence was not commonly deployed in the management of transmission systems. Today, continued cost reductions of system instrumentation and computational capacity are making real time system intelligence easier to apply to transmission system operation. Integrating this intelligence into actual operation is a growing area of innovation. These applications can enable system operators to improve system efficiency, decrease congestion costs, reduce investments in new transmission, increase return on investment of existing transmission, and reduce curtailment, as well as enhance grid reliability, reduce greenhouse gas emissions, and improve situational awareness and flexibility.[38]

Examples and evidence

Growth of Dynamic Line Rating Usage in Various Systems

Although developed in the 1970s, dynamic line rating (DLR) is being increasingly used. Various jurisdictions now utilize DLR in some fashion, including in Europe (Belgium, France, Spain, United Kingdom, Ireland); North America (Electric Reliability Council of Texas [ERCOT], Idaho Power, Bonneville Power Administration [BPA], Manitoba Hydro, New York Independent System Operator [NYISO]/New York Power Authority [NYPA]); Russia; and Australia. Several system operators that have used DLRs noted extensive cost savings and the ability to use transmission lines at a rate well above the static line rating. For example, Texas utility Oncor found that for most transmission lines, dynamic rating typically allows increased real-time capacity above the static rating 97%-99% of the time.[39] Similarly, in 2002 Manitoba Hydro experienced a dynamic line rating that was 30% higher than that of the static rating 90% of the time, which allowed the utility to defer investments in a new DC line.[40] The joint effort by the Belgium utility Elia and the French utility RTE to develop the Ampacimon surveyor program showed that 200% of the static rating could be available under experimental conditions.[41]

Growing Deployment of Phasor Measurement Units for Wide Area Monitoring

The data from the Phasor Measurement Units (PMUs) is highly accurate in terms of measurement quality and phase angles, and allows operators to improve voltage control

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and operate the transmission lines and other components closer to their true limits. PMUs also provide early warning against power system disturbances and can support system restoration. Traditionally the cost of PMUs and of the data centers needed to store the large amounts of data they produce were prohibitive. Today they are widely deployed in many countries across the EU, and in India, Thailand, China, the United States, and elsewhere.[42]

Growing Use of Real-Time and High-Resolution Market Prices

Market designs are increasingly relying on real-time and high-resolution prices, for example zonal or nodal marginal price schemes. Locational marginal prices (LMPs, also known as nodal pricing) provide highly granular price signals for a high number of "nodes" within a given electricity network. The LMP at each node reflects not only the supply and demand balance but also a congestion charge that reflects current system conditions. LMPs can help to more accurately allocate transmission costs,[43] and to provide a signal to investors as to where new generation and T&D networks could be most profitable. As Figure 7 from a 2006 simulation indicates, implementation of LMPs enable more cost efficient dispatch of generation within the PJM service territory. LMPs have predominantly been applied in Australia, New Zealand, Argentina and Chile, and in organized U.S. wholesale markets such as ERCOT, MISO, ISO-New England, NYISO, and PJM.[44] LMPs have not had similar uptake in European markets owing to concerns about the cost impacts on congested areas.[45] However, this could change, as Norway, for example, has begun to explore nodal pricing.[46]

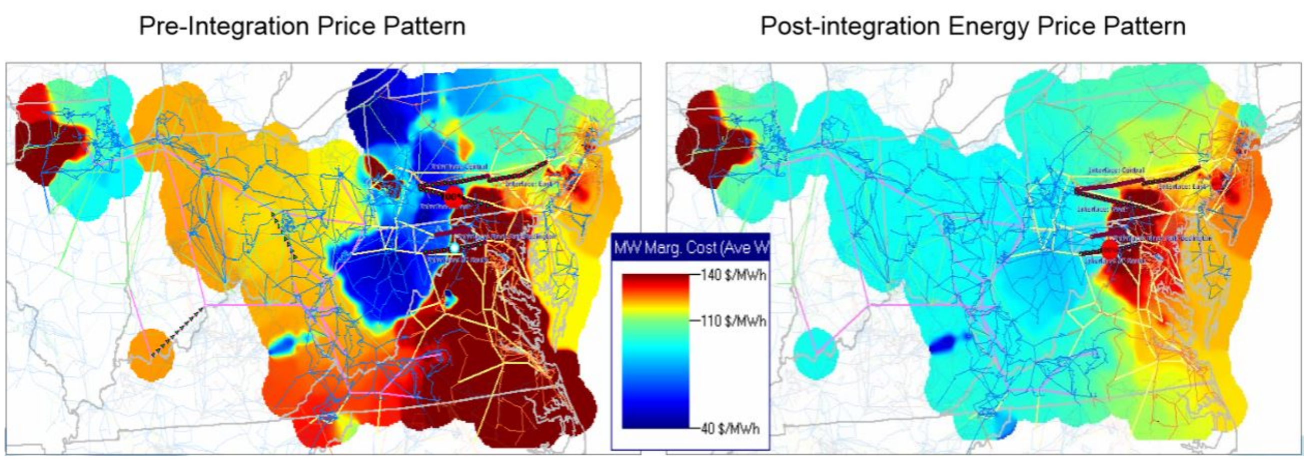

Figure 7. Simulated price patterns before and after the introduction of LMPs[47]

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Innovation #6: Coordinating Scheduling and Dispatch Across Balancing Areas

In jurisdictions where the establishment of fully organized wholesale energy markets for planning and scheduling is difficult for technical or political reasons, some of the flexibility and diversity benefits can nonetheless be gained through better coordination with adjacent balancing areas. For example, "power pools," "balancing markets," and "energy imbalance markets" (EIMs) all represent market-like agreements between well-connected adjacent balancing areas to jointly optimize dispatch across available generating capacity. The process for planning and scheduling remains as before under the jurisdiction of each balancing area, but overall dispatch is optimized to avoid "balancing against each other"[48] and results in reduced system cost.

Examples and evidence

German Balancing Market

Germany's four TSOs created a common balancing market in 2008. This market first began by netting out imbalances across borders,[49] then evolved to share a common balancing market. This allowed Germany to actually reduce reserve requirements while scaling up variable renewable energy (see Figure 8).[50]

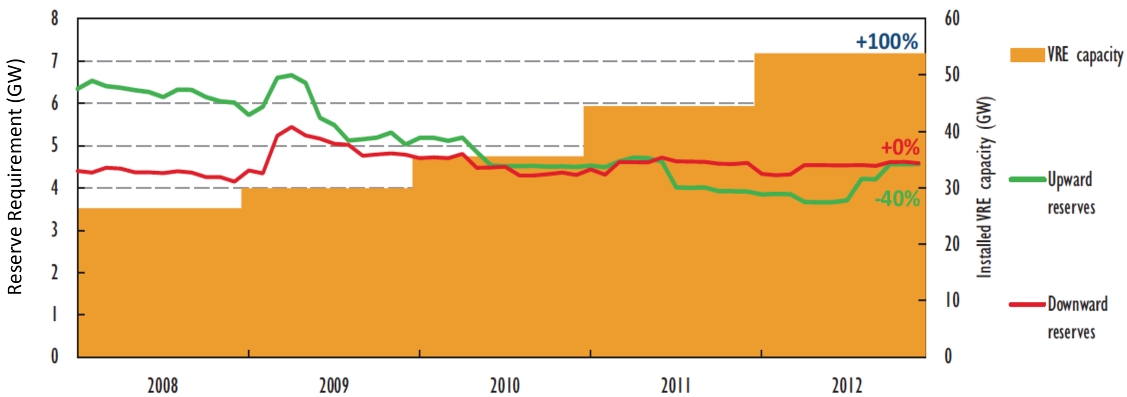

Figure 8. Requirement for frequency restoration reserves in Germany, 2008–2012

California and Adjacent Systems Establish Energy Imbalance Market

In November 2014, the California Independent System Operator (CAISO) and adjacent balancing area authority PacifiCorp began operating an "Energy Imbalance Market" (EIM) for the purpose of 1) increasing efficiency of addressing imbalance of generation and load; 2) reducing costs by accessing a wider portfolio of resources; and, 3) allowing for additional operational flexibility.[51] The operational flexibility stems from an improved situational awareness and real-time visibility of transmission capacity and the ability to dispatch resources to address congestion. Between November and December 2014, CAISO estimates $5.97 million in cost savings owing to more efficient dispatch and reduced renewable energy curtailment.[52] NV Energy intends to join the imbalance market in October 2015.[53]

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2.3 Distribution System

In the past, distribution systems have been planned around two main principles: forecasting changes in customer load and planning upgrades and extensions on that basis; and anticipating equipment replacement needs as equipment reaches the end of its useful life. These planning needs historically had to be addressed only for the purpose of passive one-way delivery of energy from the high-voltage transmission grid to the end-use customers. Distribution system planning and operation was thus quite standard and changed little over the decades. Distribution utilities did not necessarily need to be innovators, just good forecasters and planners, and could focus primarily on safety and reliability.

In transforming power systems, the distribution system is becoming a potentially semi-autonomous entity with its own balancing of variable generation and its own control over dynamic and flexible load. The distribution system must manage two-way power flows from distributed generation and storage, and must engage in new forms of interaction and control both at the DSO level and with the bulk power system at the TSO level. Some have started to call this transformed system the "active distribution network." Distribution utilities will find economic value in monitoring, collecting, analyzing, and using data in new ways, and as a consequence, will analytically model their distribution systems to a degree far beyond current practice. And utilities will use a wide variety of information and communication technologies to achieve the necessary integration of all of these elements.[54] (Note: see also Section 2.4 on Transmission-Distribution Boundary and Section 2.10 on Storage.)

Innovation #1: Distribution System Planning Processes to Better Manage Distributed Energy Resources

DSO planning in transformed distribution systems aims to proactively shape a power system with a variety of distributed energy resources. This planning aims to model and analyze the distribution system's ability to integrate future variable and storage resources, the location-specific economic values of those resources, and the potential contribution of these demand-side resources to reducing or delaying investment needs in the distribution system (wires, transformers, and/or other generators).

Examples and evidence

"Distributed Resource Planning" in California

California Assembly Bill (AB) 327 passed the California Legislature in 2013. The bill amends Public Utilities Code Section (§) 769 and requires utilities to submit Distribution Resource Plans (DRPs) that recognize, among other things, the need for investment in upgrading the distribution system to integrate cost-effective distributed generation, and for actively identifying barriers to the deployment of distributed generation. Utilities are also required to calculate the "location value" of distributed resources and the "integration capacity" of the distribution grid to connect those resources.[55]

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“Non-Wire” Alternatives in Australia

In 2013, Australia enacted a “regulatory investment test for distribution” that requires all DSOs to assess “non-wire” alternatives such as demand management and distributed generation when contemplating any network-upgrade project greater than A$1 million. DSOs in Australia are also required by national policy to produce “Distribution Planning Annual Reports” with five-year planning horizons.[56]

“Distributed System Platform” operators in New York

New York started a “Reforming the Energy Vision” regulatory proceeding in 2013 that envisions a “distributed system platform” (DSP) for integrating distributed resources. DSP planning will allow energy from distributed resources to be tracked, forecasted, and traded within the distribution system. In February 2015, after many rounds of public comments, stakeholder feedback, and analysis, the New York Public Service Commission issued an order for utilities to become DSP platform operators, with implementation plans being prepared in 2015.[57]

“Preferred Resources Pilot” in Southern California

Southern California Edison is conducting a “preferred resources pilot” to see if demand response, energy efficiency, distributed generation, and energy storage can meet over 300 MW of anticipated growth in electrical demand in a pilot region that is served by two substations. The pilot will run through 2022.[58]

“Distributed Generation Interconnection Plan” in Hawaii

In 2014, the Hawaii Public Utilities Commission ordered the Hawaiian Electric Companies (HECO) to develop and implement major improvement action plans to aggressively pursue energy cost reductions, proactively respond to emerging renewable energy integration challenges, improve the interconnection process for customer-sited solar photovoltaic (PV) systems, and embrace customer demand response programs within 120 days. In this framework the HECO notably submitted their Distributed Generation Interconnection Plan (DGIP) on August 26, 2014, in which they have developed technical solutions and actions plans to increase distributed generation interconnection capability in major capacity increments.[59]

Innovation #2: Advanced Modeling of Distribution Systems

DSOs are increasingly modeling distribution systems similarly to how bulk-power/transmission systems are modeled. Specifically, advanced modeling includes high resolution representation of distributed generation resources, new approaches to demand forecasting that account for both controllable and non-controllable loads, and the inclusion of multiple types of end-user load profiles (for example, a home with an electric vehicle). The capability to model distribution systems in this way supports many of the other innovations described in this section.

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Examples and evidence

Advanced Distribution System Modeling By German DSO EWE

German DSO EWE has modeled its entire distribution system, and this model can provide real-time responses to interconnection requests by those wishing to install distributed generation. Such interconnection requests typically take weeks or months with conventional DSO methods. EWE is among the very first DSOs (out of the hundreds of DSOs in Germany) to do such modeling, and perhaps among the first in the world.[60]

Advanced Distribution System Modeling by Utilities in the United States

Some U.S. utilities are beginning to integrate more advanced analysis and simulation software through efforts to improve open source tools such as GridLAB-D and OpenDSS. For example, American Electric Power, together with Battelle, is conducting enhanced modeling with GridLAB-D, modeling dynamic resources such as solar and closed-loop conservation voltage reduction (CVR) on distribution feeders.[61] Duke Energy Carolinas, Sacramento Municipal Utility District, Pepco, Baltimore Gas and Electric and Detroit Edison are also leading initiatives in advanced distribution modeling.[62]

Innovation #3: Advanced instrumentation and Control in Distribution Systems

DSOs are installing information and communication technologies (ICT) and supervisory control and data acquisition (SCADA) systems to monitor voltages and power flows along distribution feeders, and to enable management of two-way power flows from distributed renewable generation. Such real-time voltage monitoring was unnecessary in the past because power flows were unidirectional. One DSO expressed it this way: "monitoring distribution system voltage used to be considered akin to thinking about going to the moon in the 1950s. Maybe we can do it, but why should we?"

Now monitoring can be more readily integrated into a robust data system and network model, complete with detailed load estimations and dynamics. Increasingly, monitoring enables system control to adjust voltages in real time (sometimes called "distribution automation") such as tap-changing transformers. Historically, such monitoring and control was neither necessary nor economical at the distribution level.

Examples and evidence

Distribution System Instrumentation by German DSO EWE

The Germany DSO EWE, noted previously, has installed voltage monitoring and state estimation throughout its distribution system.

"Smart Grid Salzburg," Austria

The project "Smart Grid Salzburg" in the Salzburg region of Austria has demonstrated voltage monitoring, state estimation, and automatic tap-changing control of distribution transformers. Additionally, the "Model Community Köstendorf" includes a framework

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for active control of the distribution system with connected distributed generation and electric vehicles.[63]

Distribution Automation at Commonwealth Edison in Illinois, United States

Illinois utility Commonwealth Edison has invested significantly in distribution automation since 2011, and plans to have a total of 2600 distribution automation devices installed by 2016. The primary focus of distribution automation investments has been to isolate outages on the distribution network, with regulatory approval being granted based on benefits of reducing outages and overall duration for customers.[64]

Smart Solar District in Nice, France

The "Smart Solar District" in Nice, France combines 2.5 MW of solar, 1.5 MW of storage, 3.5 MW of load shedding capacity, and significant new monitoring and control capabilities in order to create a more autonomous local grid area.[65] This example is also discussed in Section 2.4, Innovation #1.

Innovation #4: Smart Inverters and Wind Turbines Providing Network Services

Smart inverters can provide voltage and reactive power support to local distribution feeders, and also provide "network service" (flexibility) to the ISO to help with balancing the bulk power grid (also called "Application of Advanced Inverter Functions" by some). Also, clusters of wind turbines on distribution networks can provide coordinated and dynamic voltage and reactive power support if the turbines are capable of decoupled active and reactive performance.

Examples and evidence

Controllable PV Installations in Germany

In Germany, inverters on systems larger than 30kW are required to be controllable by the TSO through power-line or GSM signals. This allows for more reliable balancing of the total system, and opens up the potential for PV systems to be dispatched to provide grid services.

California "Rule 21" Standards for Smart Inverters

In late 2014, California amended Rule 21, which provides guidelines for interconnection of distributed generation, to include requirements for smart inverters. In doing so, California became the first state in the United States to enact standards for smart inverters (at this stage, for voltage and reactive power support only). A "Smart Inverter Working Group," comprised of many stakeholders and utilities has lead the standards development process, and in 2015 was continuing to upgrade the standards, firstly in terms of developing communication and data protocols, and secondly in terms of advanced functions beyond voltage support.[66]

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Wind Turbines Providing Network Services in Ireland

The DSO ESB Networks in Ireland is doing trials for coordinated voltage and reactive power control from clusters of wind farms on distribution networks, using the decoupled active and reactive performance of the deployed double-fed induction generator (DFIG) wind turbines.[67]

Programmable and Controllable Advanced Solar Inverters in Hawaii

Hawaii Electric Companies (HECO), together with Solar City, has been working on the design of "smart inverter" functionality at customer-owned solar sites, which are expected to increase the level of solar power capacity possible on heavily impacted circuits.[68]

Innovation #5: Local Energy Markets

Traditionally, electricity markets have been implemented almost exclusively at the high-voltage bulk power system. Today, distribution-grid-level markets, facilitated by the DSO, are becoming a reality in some jurisdictions. These markets allow for local buying and selling of power, including balancing and reliability services, among local producers and consumers, independent of, or coordinated with, the bulk power system. (Also see Section 2.4 on TSO/DSO Interface.)

Examples and evidence

Local Energy Markets Pilot by German DSO EWE

German DSO EWE Netz initiated a pilot program in 2011–2013 to create and test the behavior of local energy markets within the EWE distribution territory.[69] The pilot program leveraged a network of distributed instrumentation to establish a digital energy marketplace for local buying and selling. EWE plans to build upon these pilots to develop a local energy region.

"Distribution System Platform" in New York

The New York DSP platform will function essentially as a distribution-level market place. While the specific design was still under development in 2015, the vision includes retail-level energy markets, opportunities for new retail-level energy services, demand-management on a day-ahead or real-time basis, and expanded access to system information by both customers and third-party distributed energy resources (DER) providers to help them calculate time-based and location-based economic values.[70]

Innovation #6: Wind and Solar Energy Forecasting for Distribution System Operations

Historically, wind and solar forecasting has been conducted primarily by TSOs. Today, DSOs are beginning to conduct their own wind and solar energy forecasting (typically day-ahead) to allow them to better plan and control distribution system operations.

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Examples and evidence

Solar and Wind Forecasting by Hawaii Electric

HECO is the first U.S. utility to operationalize a solar and wind integrated forecasting tool, called SWIFT, which provides a consistent bird's-eye view of wind and solar conditions across five islands, and real-time delivery of 15-minute-look-ahead wind and solar production forecasts. SWIFT provides probabilistic forecasts for both short term (next 6 hours) and long-term (up to next 48 hours) production. SWIFT integrates numerical weather prediction, local sensor data, statistical prediction models, and satellite imagery.[71]

Wind Forecasting by German DSO EWE

German DSO EWE now conducts day-ahead wind output forecasting, as it has more wind capacity connected to the distribution system than customer demand, so these wind output forecasts have become a key variable in managing distribution system operation, safety, and reliability.

Pilot Project "InovCity" in Evora, Portugal

Energias de Portugal (EDP) has developed a forecasting system that collects real-time data from distribution transformers and from customer smart meters, and provides forecasts for aggregated groups of consumers with PV generation, as well as individual consumers with PV panels. In making forecasts, real-time data can capture the spatial–temporal effect of clouds on solar generation, and consequently improve the forecasts.[72]

2.4 Transmission-Distribution Boundary

In the past, in vertically integrated monopoly utilities, there were operational and architectural differences between transmission and distribution systems, but the operation and planning of these system were performed by a single entity, whether public or private. Then, in jurisdictions that restructured their power sectors in the 1990s and 2000s, the operational and planning functions of the transmission system were assigned to newly-created transmission system operators (TSOs). From an electrical perspective there was effectively no change: power still flowed from central-station generation over the transmission network, then across substations at the transmission-distribution interface (which some call the "T-D boundary") into distribution circuits that passively transmitted energy one-way to end-use customers.

The significant changes of past restructuring were largely organizational, with the new independent TSOs becoming operators of both the high-voltage grid and the wholesale markets through which buyers and sellers of bulk power and capacity transacted. In some areas the T-D boundary also became a more significant regulatory boundary. In the United States, for example, interstate transmission and wholesale markets are regulated by the federal government (FERC), while distribution systems, and also retail markets if they exist, are regulated by state governments.

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In transforming power systems, with the accelerating proliferation of distributed energy resources (DER, which can include distributed generation, flexible/controllable demand, storage, and other distributed resources), the T-D boundary will become less distinct, more open to redefinition due to economic factors, and a valid subject of public policy debate. Questions will include what are the best market, regulatory, and technical control structures to manage this evolving boundary, in support of reliable operation, customer satisfaction, and system evolution.

Some examples of transmission-distribution (TSO-DSO) boundary innovations follow. A deeper examination of the status of these innovations is available in, for example, Zegers and Brunner (2015).[73] It is important to note that this area is relatively new, so the main examples are preliminary studies and demonstration projects, rather than full-scale implementations. New market, regulatory, and institutional arrangements will likely be necessary to realize vibrant innovations at this boundary.

Innovation #1: DSO Actions to Self-Supply Reliability Services or to Provide Reliability Services to the TSO

Typically, load variation within a DSO territory is managed primarily by procuring more or less electricity from the TSO. As such, TSOs commonly hold generation capacity in reserve to accommodate load fluctuations from DSOs. (Depending on the jurisdiction, such reserves are called, *inter alia*, regulation reserves, load-following reserves, balancing resources, etc.) Novel pilot projects demonstrate that today DER coordination can be managed in ways that reduce the need for such reserve capacity. Specifically, DERs can be coordinated to provide a larger share of these "reliability services" within a DSO territory, reducing the reliability burden of the TSO, and in some cases even to provide such reliability services back to the TSO.

One area of future innovation will be prioritizing DER reliability services between the DSO and TSO, in terms of which entity gets priority access to the services. Such prioritizations might be formalized through grid codes and tariffs. Additionally, the performance characteristics and capabilities of DERs vary, as well as the characteristics of any independent micro-grids (see Section 2.11). So the structure of contracts and tariffs will also determine the availability of reliability services.

Examples and evidence

Smart Solar District in Nice, France

As discussed above, the Nice "Smart Solar District" combines 2.5 MW of solar, 1.5 MW of storage, and 3.5 MW of load shedding capacity to create a more autonomous local grid area. This district can manage much of its internal variability without resorting to the TSO for balancing service.[74]

Decentralized Reliability Services in Denmark

In Denmark, many distribution operators have had to develop additional line capacity to facilitate net exports from Denmark to neighboring countries. In an effort to pilot one

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solution to help manage exports and large fluctuations in DG, the Danish national utility, Energinet.DK, began implementing a "Cell Controller" project in 2005. The project allows bulk-grid ancillary (reliability) services and power controls to be provided in an automated, decentralized manner. The project also allows isolated distribution grids that can maintain secure operations in the event of an emergency situation, as well as black-start recovery after the event. The Cell achieved near net power neutrality at the transmission and distribution interconnects and was able to separate from the grid. During the islanding period, the cell maintained stability until it was resynchronized with the distribution and transmission grid and resumed normal operations. Additional bulk-grid services included the provision of active power services, active and reactive power balancing operations, and voltage control services when the cell was running parallel with the high-voltage transmission system in its normal operation state.[75]

Distribution System Bidding in New York Wholesale Energy Market

As discussed in Section 2.3, the Distribution System Platform (DSP) in New York will coordinate its retail markets with the New York ISO's wholesale markets; for example the ISO could accept demand-reduction bids by the DSP in the wholesale market.[76]

Innovation #2: TSO-DSO Boundary Reliability Coordination

Effective T-D boundary coordination ensures that DER-provided services contribute effectively to system reliability. Such coordination can take several forms. For example, establishing management protocols for substations at the T-D boundary. Also, the DSO must ensure that DERs providing reliability services do not have any conflicting service commitments, such as offering the same capacity to serve both the TSO and the DSO or another entity. Coordination can also involve ensuring that DER dispatch (via direct control or economic signal) does not create detrimental effects on the local distribution system, and will require schedule and dispatch coordination at the T-D boundary between the TSO and DSO.

Examples and evidence

Smart Substations in France

One step towards T-D boundary coordination is visible in "smart substation" demonstration projects in France as part of the broader smart-grid research agenda. The French RTE "smart substation" project aims to design, build, test and operate two fully digital smart substations by 2015 in a consortium including major TSOs and DSOs. The project should result in implementation of a digital interface between the TSO and DSO.[77]

2.5 Finance, Markets, Pricing, and Cost Allocation

In the past, the question of how to set prices, organize markets, and allocate costs was driven primarily by a mix of 'least-cost' considerations, with cost being narrowly defined

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as customer electricity costs. As the conception of costs has evolved to recognize that power systems incur public costs that fall on society at large (e.g., carbon emissions, local air pollution, water stress), the design of markets, tariffs, and cost allocations has begun to change.

In transforming power systems, markets, tariffs, and cost allocation evolve in response to, and in support of, power system transformation. Four dominant modes of innovation emerge: new ways of bringing finance into overall power-sector investment; new ways of directing that finance to priority areas; new pricing mechanisms and dynamics coupled with "smart" technologies to contribute to power-system efficiency and emissions reductions, and new market mechanisms to also unlock new system efficiencies and create greatly power system flexibility.

Innovation #1: New Market and Financing Mechanisms to Unlock New Sources of Investment

Historically most power sector investment was based on a regulated rate of return on investments linked to guaranteed rates set by regulators, and finance was available on this basis. With the advent of wholesale market competition in the 1990s and 2000s in many countries, third-party project developers have been able to finance power-sector investments in an expanding number of ways. And increasingly, novel market and financing mechanisms are emerging to bring fresh sources of investment into clean energy in new markets.

Examples and evidence

Green Power Market Development in India

In India, the Confederation of Indian Industry (CII) has partnered with the World Resources Institute (WRI) to establish the Green Power Market Development Group (GPMDG) in the southern states of Karnataka and Tamil Nadu. The GPMDG brings together leading companies like Infosys, ACC Cement, Cognizant, Coca-Cola and others to pioneer new ways to cost effectively source renewable energy and work with regulators to find solutions to market barriers. To date, the GPMDG companies have made commitments to over 150 MW of wind and solar electricity contracts.

Regulatory Reform in Uruguay

Regulatory reform in Uruguay has helped to establish a reverse auctioning scheme and led to billions of dollars of new investment in the wind sector. The auction scheme was instrumental in lending transparency and credibility to the process, and by the end of 2015 it is on track to add 1000 MW of wind power.

South Africa Renewable Energy Independent Power Producer Procurement Programme (REIPPP) Auctions

In four rounds of public tenders for new renewable energy capacity, the South African Department of Energy has contracted more than $18 billion in private investment into the sector. This is in contrast to historic investment patterns, which predominantly flowed

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through the government and the partially state-owned utility, Eskom (see Figure 9).[78] Over the first three years and four rounds of bidding, average tariffs dropped precipitously for wind and solar, while locally manufactured content metrics continuously increased.

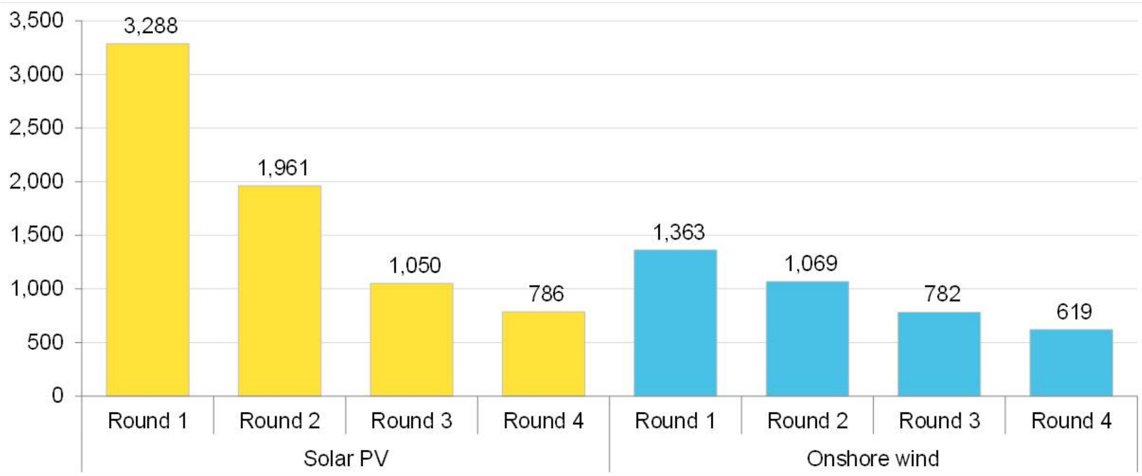

Figure 9. Solar PV and wind tariff cost declines (South African Rand/MWh) by bidding round for South Africa REIPPP

Innovation #2: Frameworks for Prioritizing Investment in System Resources

Innovations in prioritization frameworks are serving to direct investment to priority and least-cost assets in a variety of ways. Numerous examples are emerging of how market design and tariffs can influence investment patterns, and many are referenced throughout this chapter. (In particular, see the examples in Section 2.1 on planning frameworks, Section 2.6 on tariffs, and Section 2.7 on market designs for flexible generation.) There are also a variety of innovations emerging that prioritize resources according to least-cost or policy-driven criteria.

Examples and evidence

California's "Loading Order"

California's "loading order" has accelerated the transformation of the state's power system during the last decade by establishing a prioritization of resources for power system procurement. Specifically, the loading order requires utilities to meet electricity demand in the following priority sequence: (1) energy efficiency and demand response; (2) renewable resources; and (3) clean and efficient natural gas generation. California has thus established energy efficiency/demand response and renewables as the highest priority resources for new procurement.

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Integrating Energy Efficiency into Electricity Planning in Northwest United States

Pacificorp, a U.S. utility operating across six states, undertook a complex system-wide integrated resource planning process that integrated five state Integrated Resource Plans (IRPs), various renewable portfolio standards, and other state-specific policies. The Pacificorp approach was unique in the sense that energy efficiency (often considered a load modifier) was assessed as a supply resource, allowing it to be compared with other supply options in the IRP model. Consideration of energy efficiency as a supply resource led to cost-saving energy efficiency measures that accounted for a large portion of electricity supply in the final IRP.[79]

Innovation #3: Customer Pricing Reform to Unlock System Behaviors

Historically, electricity prices were fixed year-round, contributing to rigid, inelastic consumption patterns and sharp system peaks. Pricing patterns began to evolve, for example to incentivize efficiency (e.g. tiered structures) or to reduce peak demand (e.g. peak pricing). More recently, cost declines in smart metering and customer-facing devices are unlocking new possibilities to send dynamic prices to consumers to support more elastic energy demand, and to make the electricity demand much more flexible in response to system and market conditions. (See also demand response innovation #2 in Section 2.6.)

Examples and evidence

Time-of-Use Rates in Ontario

Ontario has rolled out over 4 million smart meters and implemented time-of-use energy charges for its entire residential customer class, with the goal of encouraging conservation during periods of peak demand and shifting load toward mid-peak and off-peak periods. Ex-post analysis has shown a steady pattern of load shifting behavior across the service territory, with observed average peak demand reductions of up to 5.6%.[80]

Locational Deployment Incentives for Distributed Generation Deployment in New York

The New York State Energy Research and Development Authority (NYSERDA) offers a 1.25 multiplier on incentive payments for distributed PV and biogas systems that are deployed in pre-determined "Strategic Locations" within the New York electric system (see Figure 10[81]). These locations are deemed strategic for deployment of new

Figure 10. NYSERDA Targeted Solar Zones, Manhattan, New York City, United States

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capacity as prospective systems would provide amplified benefit to the local electric distribution system, such as congestion reduction or voltage boosting.[82]

Innovation #4: Wholesale Energy Market Reform to Unlock System Behaviors

By and large, wholesale energy markets were designed before it was economical to add large amounts of demand response, wind power, or solar power. As such, prices, scheduling, and bidding rules were not designed to be inclusive of all of these resources. Innovations are arising to unlock new system behaviors and include new participants.

Examples and evidence

Intra-hour Market Scheduling via U.S. FERC Order 764

The Federal Energy Regulatory Commission, which governs interstate transmission ownership and electricity exchanges in the United States, recently approved an order requiring intra-hour scheduling of wholesale markets. This change to operational protocols mitigates several known market inefficiencies and also reduces barriers to integrating increasing quantities of variable renewable energy.

Intra-hour Market Scheduling via India CERC Order 127-2011

Partly in response to growing renewable energy supply and increasing needs for flexibility, the Indian market is moving to sub-hourly scheduling.[83] This regulation is expected to lead to more gradual of ramp rates, which currently “kink” at hourly boundaries. More gradual ramps up and down will be easier to manage for market participants, especially utilities as they manage imbalances. The regulation will also encourage participation of renewable energy in power exchanges, and will bring power exchange prices into closer alignment with the “Unscheduled Interchange” system, which is used to provide frequency discipline. Finally, this regulation will be advantageous for peak load management as Eastern & Northeastern states, as they have earlier sunsets compared to southern states.

Demand Response Bidding in the PJM Wholesale Market

In the Eastern U.S. wholesale energy market PJM, demand response resources can bid into energy (day ahead, real time), ancillary service (e.g., synchronized reserves, day ahead scheduling reserve, regulation), and capacity markets. Approximately 3,000 MW of economically-responsive demand response was participating in the energy and ancillary service markets as of December 2014, while over 9,000 MW of demand response cleared in the PJM capacity market.[84]

Innovation #5: Market Frameworks for Ramping Capacity

Some TSOs are creating new market frameworks specifically to help them handle intra-day ramping needs, beyond the normal response of day-ahead and real-time markets to

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meet ramping capacity needs. Such frameworks may also include cost-allocation provisions to cover additional cost burdens created in these frameworks.

Examples and evidence

Flexible Ramping Product in California

The California ISO plans to operationalize in 2015 a new "Flexible Ramping Product" that will create a 5-minute real-time market for flexible ramping capacity that can include variable renewable generators. This market will pay generators to not generate during specific intervals, so that they may turn on during later periods of high up-ramping needs. This market compensates generators for their lost revenue from not generating, and pays a premium in addition to market price for when they do generate. (And the reverse as well, for down-ramping needs.) The ISO has designed this market to allow wind and solar generators to participate and benefit from such premiums. The ISO also contemplates the case where solar may be paid through this market mechanism to ramp-down in a more controlled fashion in the late afternoon, to reduce the overall system ramping rate.[85]

Innovation #6: Market Frameworks That Allow Zero or Negative Prices to Efficiently Provide Renewable Energy Curtailment Signals

Power pricing that reflects real-time oversupply—in the form of zero or negative prices—can improve overall system performance. Power system operators around the world have used curtailment as a strategy for managing the variability of solar and wind power. Some curtailment is "ordered" by the TSO, while other curtailment is considered "economic curtailment," that is, self-curtailment in response to economic signals. With the emergence of market frameworks in many power systems that allow zero or negative prices, such "economic curtailment" of solar and wind generators is increasingly common, relative to "ordered curtailment."[86] (Note: In some markets, subsidies or other policy provisions might still make wind or solar operation profitable at zero or negative power prices.)

Examples and evidence

European Wholesale Markets Pricing

Negative prices are allowed in European wholesale markets,[87] and serve as a useful gauge of power system flexibility. Specifically, tracking the number of hours per year in which prices are negative is emerging as one data point for the ability of the system to capture maximum value from variable renewable energy.[88]

Locational Marginal Prices (LMPs) and "Dispatchable Intermittent Resources" in the MISO System

Since mid-2011, the Midcontinent Independent System Operator (MISO) has begun to transition from manual or 'ordered' curtailments to economic-based curtailment. The 'Dispatchable Intermittent Resources' program requires wind plants operating on or after

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April 2005 to bid into the real-time market, contributing to the formation of LMPs (also called "nodal pricing").[89]

Negative Pricing in the Indian National Grid

The India Central Electricity Regulatory Commission issued regulations in 2014 that allow negative pricing in case of deviations of 12% above scheduled generation.[90] The intent is to disincentivize continued production during periods of oversupply. To account for temporary deviations by renewable energy generators, CERC has also proposed to allow a moderately larger number of, and more frequent revisions to, the schedules of renewable energy generators. In this way, the provision aims to provide both a commercial signal to conventional generation for better balancing of variable generation, while also providing a commercial incentive for renewable energy generators to implement accurate forecasting systems.

Innovation #7: Decoupling Revenue from Electricity Sales

When utility revenues are tied only to volume of energy sold, there are few incentives for utilities to promote efficiency. Throughout the world, regulators have increasingly been employing various forms of revenue decoupling—strategies which attempt to equitably break this link between volume of energy and revenue collected from ratepayers. Decoupling strategies can facilitate greater investment not only energy efficiency, but also other energy services, such as demand response and distributed generation.

Examples and evidence

The Revenue-Incentives-Innovation-Outputs (RIIO) Model in the UK

UK regulators have instituted a ratemaking structure for electric and gas utilities in which revenue is a product of "incentives + innovation + outputs." This regulatory framework allows for a broader set of performance metrics to be used for utility ratemaking. An important feature of the RIIO framework is that it locks in a set of performance metrics for a period of 8 years to provide a degree of certainty, facilitating planning for utility investments.[91]

Decoupling of Revenue from Sales in California

Steps toward decoupling utility revenue from energy sales in California were first taken in the early 1980s. Since then, the decoupling framework has evolved over the years. Under this framework, utilities submit their revenue requirements and estimated sales to regulators, who then set power rates by regularly applying adjustments to help ensure that utilities collect no more and no less than is necessary to run the business and provide a fair return to investors. Any excess revenue gets credited back to customers, and any shortfall gets recovered later from customers.[92]

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2.6 Static & Dynamic Load

In the past, power system load was typically considered a relatively predictable quantity, based on known profiles. Forecasting of load happened years in advance. To the extent demand was dynamic (responsive to intelligence and control), it was largely for reliability purposes, such as using price incentives to reduce aggregate demand during critical system peaks.

In transforming power systems, dynamic load is becoming more economic to deploy and manage. (The concept of dynamic load can also be denoted by several alternate names, such as "flexible load," "load flexibility" or "demand response.") A variety of technologies (often grouped under the blanket term "smart grid technologies") are unlocking the innovations necessary to make a variety of loads dynamic. These innovations link end-use consumers with various aspects of grid services and operation, for example the provision of flexibility and peak shaving. Widespread deployment of smart meters and other enabling technologies can facilitate new pricing models, new patterns of demand and customer behavior, and new sources of load flexibility.

This means that load can be adjusted in magnitude, or time-shifted to other periods in response to a variety of system conditions. Such adjustments can originate from the customer, from the system operator, or as automated responses to a price signal.

At the same time, in transforming power systems, the non-dynamic ("static") part of load is also being aligned more with the needs of power system variability and flexibility through new perspectives on energy efficiency. Improvements in the energy efficiency of a wide variety of end-use equipment can be tailored to the evolving needs of power systems, for example reducing demand at certain times of day, or providing thermal storage (see Section 2.9).

Historically, the main concern of utilities was to reduce peak load. But demand adjustments in transforming power systems no longer occur just at peak-times, but can occur equally at off-peak times as well. Increasingly, the reliability imperatives of power systems mean that greater flexibility is need during times of low load but high variable renewable output. In addition, in some jurisdictions, the concept of "overgeneration" is emerging, which can mean too much solar power at peak periods, coupled with an inability to ramp down conventional power plants. As overgeneration occurs, the proper response is to actually increase load at peak times, for example through lower real-time prices during peak times.

Innovation #1: Incorporating Dynamic and Static Load Into Planning

Demand-response, load-reduction, load-shifting, and other "demand-side resources" are now being incorporated into long-term generation and transmission planning models, which formerly only considered supply-side resources and static load forecasts. The models incorporate the contribution of these "demand-side resources" to overall system reliability, flexibility, ramping needs and capabilities, and reserve requirements.

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Examples and evidence

California's Long-Term Procurement Planning

California's long-term procurement planning process takes account forecasts of demand-side resources on 10-year time horizons. The flexibility of these demand-side resources, including distributed generation, storage, demand response, and energy efficiency, can be considered in setting an overall level of required flexibility and capacity from conventional generation resources like natural gas. More and more, planning, along with the evolving demand-side forecasting that go along with it, is taking account the changing and more complicated nature of load. Planning can also take into account the impact of future time-of-use rates on load.[93] (See also Section 2.3 on distribution system and Section 2.10 on storage.)

French ISO RTE Generation Adequacy Report

Every two years, the French TSO RTE performs a forecast assessment to anticipate any electricity supply-demand imbalance in the country's electricity system. Demand response is increasingly considered in the developments of this outlook.[94]

Ontario Power Authority's Power System Planning

Ontario Power Authority's system planning takes a long-term, province-wide perspective, examining possibilities for future electricity demand and how it can be met through conservation (including demand response), generation, and transmission options.[95]

South Africa Department of Energy's Integrated Resource Plan (IRP)

As discussed in Section 2.1, the IRP is South Africa's national electricity plan, which directs the expansion of the electricity supply by identifying the investments in the electricity sector that allows the country to meet the forecasted demand with the minimum cost to the country. Demand Response options are included in the IRP.[96]

Innovation #2: Allowing Dynamic Load (Demand Response) To Bid Into Wholesale Markets

Dynamic load, or demand response (DR), can be allowed to bid into wholesale markets. In various jurisdictions, demand response be able to bid into energy, capacity, and ancillary markets on a commercial basis. Often, market rules and regulation may be adapted or enhanced to allow for the more effective participation of demand response. For example, auction period or intervals may be reduced, to enable dynamic load a shorter window of forecasting the degree to which given loads will be adjustable during the times needed.

Examples and evidence

Demand Response as a Reliability (Ancillary) Resource in Germany

In Germany, demand response (interruptible loads and emergency generators) can participate in the ancillary services market. Interruptible loads can also participate in a program called Ordinance Governing Interruptible Loads. In 2014, there was about 0.9

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GW of demand response being bid into markets on a monthly basis. There are no special rules for demand response. However, aggregating several loads and/or generators is permitted, so demand resources with a limited availability may participate through an aggregator. The Ordinance Governing Interruptible Loads requires German TSOs to collectively tender specified quantities of dynamic load. The requirements in 2014 were 1.5 GW of "immediately interruptible" loads (1-second activation) and 1.5 GW of "quickly interruptible" loads (15-minute activation).[97]

Demand Response Bidding in PJM (United States) Market

As noted above, in the PJM system, demand response can bid into energy, ancillary, and capacity markets. In 2014 registered demand response resources across these markets constituted about 5% of the peak load of the system.[98]

Demand Response as a Reliability and Ramping Resource in Texas

Under the jurisdiction of the ERCOT ISO in Texas, demand response can participate in the ancillary services market and in a reserve program called Emergency Response Service (ERS). ERS aims to increase system reliability during power system emergencies and participation is exclusively limited to demand response resources (interruptible loads and emergency generators). In 2014, demand response provided about 700 MW to ERS. Interruptible loads can also participate in the energy and ancillary services markets. The ancillary market is divided into three different products: Regulation Reserve, Responsive Reserve and Non-Spinning Reserve. Responsive Reserve, which contracts more than 1 200 MW of interruptible loads on average each year, is most relevant. In 2014, ERCOT's total demand response capacity that could be used for system reliability was approximately 2.8 per cent of the annual peak load of 67 GW.[99]

Innovation #3: Demand Response to Support Reliability Within Distribution Systems

Demand response can be controlled by a DSO to self-supply reliability services. (See also Sections 2.3 and 2.4.) This can reduce reliance on the TSO for reliability services, and consequently reduce the needs for total generation held in reserve by the TSO for grid balancing (reserve margins).

Examples and evidence

Automated Demand Response in the U.S. Pacific Northwest

The Northwest Smart Grid Demonstration Project targets automatic dispatch of customer DER, including demand response resources such as electric water heaters.[100]

Con Edison Demand Response Programs in New York City

Con Edison, the utility for New York City, administers peak shaving and contingency-based demand response programs to manage energy usage from May to September. These programs are designed to cost effectively maintain reliable service on the Con Edison electrical distribution system.[101]

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Innovation #4: Time-Of-Use Pricing to Increase Demand Responsiveness to Power System Needs

Time-of-use pricing models are more and more being considered as key ways to shape the responsiveness of dynamic load according to the needs of power system flexibility and reliability, rather than simply peak-load management. Also, time-of-use pricing can help meet system ramping needs for integrating variable renewables. For example, during times of high solar output, prices may fall to lower levels to avoid an "overgeneration" condition, while during a period of high system ramps (swings in load or supply), for example as the sun is setting and solar output is diminishing, higher prices may encourage load reduction and thus reduce the required ramp rates.

Examples and evidence

U.S. Dynamic Pricing Pilot Programs

In the United States in recent years, a number of dynamic pricing pilot programs have been implemented. These include California's Statewide Pricing Pilot (SPP) and Connecticut Light & Power' Plan-it Wise Energy Program (PWEP). Such efforts have also been led by Pepco, the utility in Washington, D.C. Today, Oklahoma Gas & Electric is achieving significant participation of residential customers through its aggressive opt-in program Variable Peak Pricing.[102]

Innovation #5: Equipment Codes and Standards

End-use equipment is being designed to respond to "smart grid" commands, to participate in energy-trading, to serve as demand-response resources, and to respond autonomously to grid conditions. A number of countries are currently developing standards to unlock greater appliance responsiveness.

Examples and evidence

Smart Air Conditioners in India

New cooling units sold in India starting in 2015 are encouraged, through standards, to have smart switching capability.[103] This is expected to increase total reliability of the power system as air conditioning penetration grows.

Air Conditioner and Heat Pump Labeling in Korea

Since October 2014, Korea has implemented an appliance labeling program to support smart cooling units and heat pumps.[104] This program aims to increase customer adoption of intelligent appliances.

Smart Appliance Standards in Australia and New Zealand

Under the Australia and New Zealand standard AS/NZS 4755, appliance controllability is encouraged for air conditioners, pool pump controllers, water heaters, and electric vehicle charge controllers.[105]

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Draft IEC International Standards for Smart Appliances

The International Electro-technical Commission, an international standards setting body, is preparing a draft specification for DR-ready appliances. This specification, being conducted by the working group "TC59/WG15," would broadly cover many appliances on a global level.[106]

Innovation #6: Integrated Demand-Side Management

"Traditional" DSM approaches of the past commonly focused on contracting with customers to reduce peak demand. "Transforming" DSM approaches now emerging are marked by a wider range of performance characteristics, leveraging flexible and intelligent load with storage, managed charging of electric vehicles, and building energy management to manage a customer load in a least-cost manner given tariffs and market structure.

Examples and evidence

Integrated DSM in California

The California Public Utilities Commission has initiated a regulatory proceeding focusing on Integrated DSM. The proceeding aims to encourage building energy management solutions via the integration of comprehensive energy management technologies and strategies. The goal is to use customer education and behavior changes to reduce load.[107]

Innovation #7: Conservation Voltage Reduction

The goal of conservation voltage reduction (CVR) is to enable distribution feeders to be operated at the lower end of the prescribed voltage range as required for system reliability. CVR is enabled by modern software, hardware, and communication solutions. Operating distribution feeders at the low end of the prescribed voltage range reduces electric demand and energy consumption compared to operating at the midpoint of the prescribed voltage range. CVR is selectively employed to dynamically transform the distribution network into a flexible load resource, reducing the need for investments in new generation resources.

Examples and evidence

Conservation Voltage Reduction in Maryland (United States)

The Baltimore Gas and Electric CVR program will reduce peak demand by 85 MW and energy consumption by 250 GWh. Novel algorithms also promises to allow wider deployment than previous solutions that required relatively greater investment in grid hardware.[108]

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2.7 Flexible Generation

Flexibility of generation—from both conventional generation and variable renewables—is a fertile area of innovation. The need for flexibility in power systems with high levels of variable renewables is widely recognized. This section illuminates some key areas of innovation in flexible generation that are emerging in support of power system transformation. This section is divided into two parts: Part 1 addresses flexible conventional generation, and Part 2 addresses system flexibility from variable renewables.

PART 1: FLEXIBLE CONVENTIONAL GENERATION

In the past, the historic framework for planning for and operating a power system distinguished three generation types—baseload, intermediate, and peak—based on the duration of plant utilization across the year and marginal cost to operate.[iv] In this construct, conventional baseload generators such as coal were designed to be operated at full output for much of the year, and were not considered a source of system flexibility. Although they are able to cycle (i.e., change output), such as to provide frequency response and operate at partial output, cycling was minimized due to concerns about damages and/or reduced equipment lifetimes that plants can incur.

In transforming power systems, in which variable renewable energy does not generate power conforming to the base load-intermediate-peak framework, the historic framework is less useful for determining dispatch practices and investment priorities. The generation with the lowest operating cost is more likely to be wind and solar, but these plants do not run the full year so cannot be considered "baseload" based on their duration. Because the wind and solar generation displace marginally more expensive units that had been baseload, those plants are operated for fewer hours of the year and come to more closely resemble "intermediate plants" (see Figure 11). [109] Moreover, to remain cost-competitive in dispatch, these thermal generation plants would now be expected to have the operating characteristics of plants that meet intermediate loads, such the ability to cycle (see Figure 12).[110] As a result, thermal plants such as coal, combined cycle natural gas, and even nuclear, are being designed and retrofitted to provide system flexibility.

[iv] Baseload plants, such as coal, nuclear, and some hydro, typically had the cheapest operating costs and were operated at full output and rarely turned off. These generators were designed to be operated in this manner. Intermediate plants, more typically combined cycle natural gas, were operated to meet demand for significant portions of the year, but not continuously, such as to meet daytime load. Peaking plants, such as gas-fired combustion turbines, are designed to operate flexibly—at a price—and are typically dispatched only during peak demand periods.

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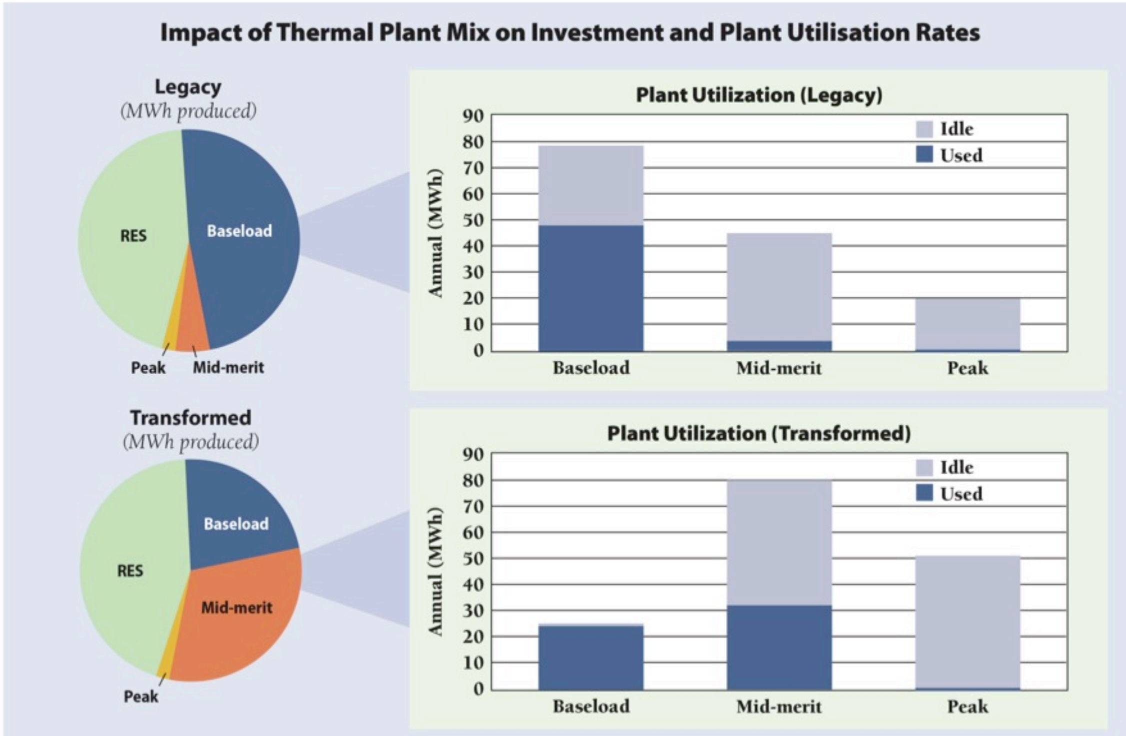

Figure 11. Illustrative impact of thermal plant mix on investment and plant utilization rates

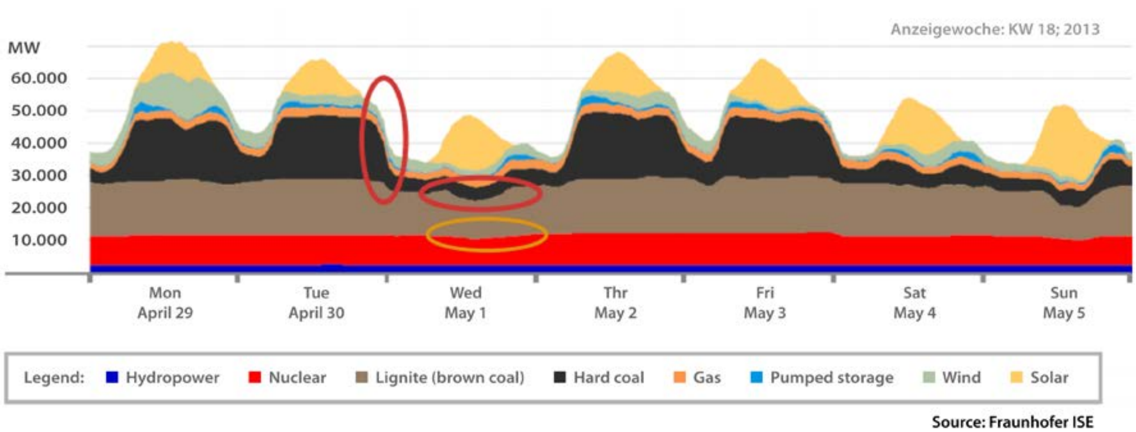

Figure 12. In Germany, coal plants increasingly provide ramping flexibility (red ovals), and even nuclear plants provide some flexibility (yellow oval)

Innovation #1: Flexibility From Coal Plants

Coal plants are now used to provide system flexibility (i.e., able to cycle on and off, reduce minimum generation levels, and follow changes in net load).[111] Aspects of flexibility include improving ramp rates, reducing minimum generation levels, coming

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back on-line quickly after a shut-down, and more closely following dispatch signals. This flexibility requires at least some hardware modifications as well as extensive modifications to operational practice. Operational changes include comprehensive inspections and training programs, controlled temperature ramp rates, repair process and program for each possible cycling-related failure, changed layup procedures, and greater tolerance for higher forced outage rates.[112]

Examples and evidence

Flexibility Price Premiums for Coal Plants in Jilin Province, China

At the end of 2013, wind power in Jilin Province represented approximately 16% of total generation capacity in the province.[113] Wind power curtailment rates are also significant, reaching 33% in 2012 and 20% in 2013. For reference, curtailment is typically less than 1% in countries like Germany and Denmark, to 2%–3% in many parts of the United States. The curtailments in Jilin often occur during periods of high supply relative to demand, such that exporting excess supply is not an option due to transmission constraints and inflexible supply in neighboring jurisdictions.[v] To improve the ability for the power grid in Jilin to integrate wind power, China State Grid is conducting a pilot program to provide a price premium to coal plants that reduce their output below 52% of capacity. The premium is structured as a higher per-kWh power price when the power generated is occurring at output levels below 52%. The incentives are intended to counteract the increased costs of cycling that stem from fuel efficiency and added wear and tear.[vi]

South Africa: Majuba Coal Plant[114]

Built in 1982, the Majuba plant provides 4,110 MW of coal-fired capacity to the region around Amersfoort, South Africa. The plant with six units of around 600–700 MW each was designed to enable quick start-ups and load following with a simple arrangement of wall panels, connecting pipes, and tube banks to allow for expansion and to reduce stress. To reduce thermal fatigue, a significant impact of cycling coal plants, wall panels with differing temperatures are not connected via welding and the flue gas pattern is arranged in such a way as to mitigate tube erosion. These features enabled Majuba to compete effectively in the South African Power Pool as a two-shift power plant despite being originally designed for baseload power.

Flexible Plants in Denmark

Many coal power plants in Denmark are able to ramp down to just 10% of rated output, the lowest minimum output level in the world.[115] Denmark has been designing its power

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[v] Jilin has a high capacity of wind power, about 4 GW, which is about the same capacity as its minimum daily power grid load of 4.7 GW. Peak daily load is 7.2 GW. Statistics from China State Grid, December 2014.

[vi] Equipment failures and maintenance costs increase with increased cycling. The second phase of the Western Wind and Solar Integration Study (WWSIS-2) directly addressed the impacts of high wind and solar penetration levels on thermal plant cycling. For a 33% RE scenario, WWSIS-2 concluded that from a single generator perspective—typical operating costs, including fuel, are $20–$40/MWh, whereas increased operations and maintenance costs due to RE-induced cycling were $0.5–$1.3/MWh.

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system with flexibility in mind since the late-1990s, and has been explicitly designing coal plants for flexibility over the past 10–15 years.[116]

Innovation #2: Flexibility From Non-Coal Plants

Other (non-coal) thermal plants—large power plants as well as small-scale micro combined heat and power units—are also being newly designed for or retrofitted to provide flexibility.[117] Examples of thermal generation that are designed for heightened flexibility include aeroderivative turbines and reciprocating engines.

Examples and evidence

Flexible nuclear plants in France

When considering options for flexible generation, nuclear is not typically a first choice. However, in France nuclear plants are being used to provide both frequency response (primary and second controls) and load following services.[118] Since more than 80% of demand being is met by nuclear generation, the national operator requires some level of load-following flexibility to qualify for a license, which may also include provisions for the total number of load cycles allowable based on plant design. It is important to note that operating nuclear plants at less than maximum load has been demonstrated to increase the occurrences of unscheduled outages.[119] Diligent operations and maintenance protocols are needed to provide for safe operation, including monitoring control rod mechanisms, temperature and pressure fluctuations.[120]

Flexible Combined Cycle Gas Plant in United Kingdom

The Sloe Centrale combined cycle plant was built in 2009 with flexibility explicitly factored into its design, enabling daily start-ups.[121] Consisting of two 435-MW units, the plant also has quick-start capabilities enabled by Benson-type boiler. An air preheater is used to optimize efficiency during partial load. The units use a unique design, known as a single shaft configuration with its turbine, generator, and steam turbine along a central axis, allows for ramping from 0 to full capacity in 30 minutes.[122]

Flexible Gas Plants in Denmark

Many combined cycle natural gas power plants in Denmark are able to ramp up and down at speeds faster than equivalent natural gas plants in other countries. Danish Energinet (2014)[123] says that many flexible natural gas plants (commissioned in recent years) can ramp at significantly higher rates than more conventional “inflexible” gas plants. (For reference, IEA (2014) lists a typical “flexible” CCGT ramp rate as 6–15% per minute.[124])

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PART 2: SYSTEM FLEXIBILITY FROM VARIABLE RENEWABLE ENERGY GENERATION

In the past, variable generation such as wind and solar were not considered dispatchable; instead that generation was treated as nonresponsive, accepted at full output and unable to serve as a balancing resource.

In transforming power systems, changes to wholesale power market design in many jurisdictions now allow variable generation to bid into the market and be dispatched, and be treated similarly to conventional plants. Also, advancements in inverter technologies allow wind plants to provide the full range of balancing services.[125]

Innovation #3: Variable Generation Serves as a Dispatchable Resource

Increasingly, jurisdictions with high shares of variable renewable energy are demonstrating that variable renewable energy generators can be operated in ways similar to dispatchable resources.

Examples and evidence

Control Centres for Renewable Energy in Spain

Red Electrica de Espana (REE) was the world's first TSO to develop centralized, dedicated monitoring and control of variable renewable energy plants in 2006. Currently, the system operator is able to control the dispatch of up to 96% of the Spanish wind power fleet, change its aggregate production to any given level within 15 minutes and drastically reduce curtailment.[126]

Flexible Ramping Product in California

As discussed in Section 2.5, Innovation #5, the California ISO plans to operationalize in 2015 a new "Flexible Ramping Product" that will create a 5-minute real-time market for flexible ramping capacity that can include variable renewable generators. This market will pay generators to not generate during specific intervals, so that they may turn on during later periods of high up-ramping needs. This market compensates generators for their lost revenue from not generating, and pays a premium in addition to market price for when they do generate. The ISO has designed this market to allow wind and solar generators to participate and benefit from such premiums. The ISO also contemplates the case where solar may be paid to ramp-down in a more controlled fashion in the late afternoon, to reduce the overall system ramping rate.[127]

Innovation #4: Grid Services From Variable Renewable Energy Plants

Increasing amounts of variable renewable energy requires closer attention to ensuring that voltage, frequency, and power quality remain within approved constraints. Accordingly, innovations are emerging such that variable renewable energy generators can provide grid services such as voltage and frequency support.

Examples and evidence

Enhanced grid services from variable renewable generators in several U.S. grids

The largest independent system operator in the United States, PJM, has asked U.S. federal regulators to approve a requirement that all new wind and other variable generators have advanced inverters that can provide dynamic reactive support to control frequency and voltage.[128] Xcel Energy in Colorado requires many wind turbines to be on automatic generation control, which allows the system operator to send computer signals to the turbine to maintain the balance of supply and demand. ERCOT in Texas requires wind turbines to provide autonomous changes in output to control grid frequency—a speed of response faster than automatic generation control.[129] Similar requirements for PV plants are also being adopted.[130] For example, the California Public Utility Commission modifications to interconnection specifications require distributed PV to have smart inverters that monitor grid conditions, autonomously provide local voltage support, meet ramp rate requirements after an outage, and ride through frequency and voltage events.[131]

Voltage and Reactive Power from Wind Farms in Ireland

Wind turbines in Ireland currently have the technical capability to provide voltage and reactive power support to the grid, but have not yet been called upon to provide this capability. As noted in Section 2.3, the DSO ESB Networks Ireland is doing trials for coordinated voltage and reactive power control from clusters of wind farms on distribution networks, using the decoupled active and reactive performance of the deployed DFIG wind turbines.

2.8 Integration with Heating and Cooling

In the past, heating and cooling systems for industrial, commercial, and residential purposes were commonly planned and operated without consideration for electric system impact. In those cases where heat and power were integrated, for example with combined heat-and-power (CHP) plants, district heating systems, or distributed electric water heaters, this was done primarily to improve energy efficiency or to accommodate inflexible base-load generators.

In transforming systems, integration of power systems with heating and cooling, and innovations at the boundary between electricity and thermal systems can unlock other important system benefits. Potential benefits include increased system flexibility through dispatchable loads and stored energy. This flexibility can allow for the incorporation of more variable renewable energy, reduced costs, and reduced peak system loads. CHP plants will continue to remain key elements of transformed power systems (see Box 1), but there are also many opportunities to use heating and cooling loads, thermal storage, and district heating systems in new ways. In traditional power systems generation is designed to meet electric load only. In more advanced power systems, integration and management of thermal loads into generation scheduling can increase flexibility.

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Innovation #1: Thermal Loads and Storage for System Flexibility

Control of thermal loads and thermal storage have long been utilized to shift daytime loads to nighttime for cost savings and to reduce system peak loads. This same concept is now being utilized in shorter time intervals and at different times of day to support balancing of variable renewable energy generation, cost reductions, demand response, and decreased system peak loads in conjunction with smart communications and controls.

Thermal Storage Using Electric Water Heaters in Minnesota

Electric water heaters in 70,000 homes in Minnesota are being transformed into a dispatchable thermal battery that can be utilized when the output of wind farms is high and power prices are low.[132] Historically these heaters —equivalent to one gigawatt-hour of energy storage— have been utilized by Great River Energy as night time storage to accommodate inflexible base load power, with each heater turning on at 11:00 PM and off at 7:00 AM, and the produced hot water being used during the day. A large increase in wind generation since 2007 has increased the value of these water heaters for more varied usage patterns. Leveraging communication technology upgrades, these water heaters are being used both for wind integration and potentially for other grid services.

Thermal Storage Using Electric Water Heaters in Ireland, Germany, and Latvia

A similar program is just beginning in Europe managed by the Real Value continuum with a $7.2 M Euro grant.[133] The project will replace electric space and water heating units in Ireland, Germany, and Latvia with more efficient and remotely controllable units.[134] The utility will utilize these units for renewable energy integration, demand response, and ancillary services as well as to forecast load.[135]

Flexible CHP and District Heating in Denmark

Some CHP plants can vary their electrical and/or heat outputs to support balancing and to balance systems with significant variable renewable energy. The ability to provide flexibility depends on the specifics of the plant. For example, in a “back-pressure” CHP plant the ratio between heat and electricity is fixed and output flexibility is very limited. In an “extraction” CHP plant the ratio between heat and electricity can be varied thus allowing for much more flexible output.[136] Denmark has one of the highest rates of CHP use in the world, generating over 60% of its electrical energy and about 80% of its district heating needs from CHP systems.[137] The transition of the energy system in Denmark has been gradual over the last several decades from a heavy dependence on fossil fuel to a focus on local CHP and district heating systems and wind energy (See Box 1).[138] The CHP and district heating systems provide dispatchable generation as well as thermal energy storage. CHP plants are required to participate in the spot power market, creating a financial incentive to offer system flexibility. For example, during periods of significant wind generation and consequently lower prices, CHP plants can reduce electrical output to minimum and instead rely on thermal energy storage or electric boilers powered by purchased electricity to provide district heating.[139]

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New Mechanisms and Programs for Utility Control of Household Thermal Loads

Utility control of household thermal loads to reduce system peaks has been a long-standing feature of power systems. Over 50 utility programs exist already in the United States to provide electrical system benefits through automated individual thermal systems control.[140] These programs target a diverse range of loads such as electric water heaters, thermostats, air conditioners, and pool pumps. For example, in Colorado Xcel energy will give customers a $40 per year credit for installing a "saver switch" on their air conditioner. The switches are operated by the utility 10–15 days a year during peak electrical system loads.[141] Traditional programs of this type are being expanded in new and innovative ways. For example, a recent study of three utility programs for Nest smart thermostats successfully demonstrated an average 55% air conditioning electrical peak load reduction.[142] The Nest thermostats provide a new way for a utility to control a customer's air conditioner that doesn't require the utility visit the customer's house and install a separate smart switch directly on their air conditioner.

Automated Demand Response in California

California's new Title 24 building codes require all new or retrofitted thermostats, HVAC systems, lighting control systems, and automated building energy management systems to be capable of accepting automated demand response signals.[143] The Open Automated Demand Response[vii] (ADR) Alliance helped create an open source communications protocol that many companies are utilizing to design devices to meet this requirement and utilities in California are offering demand response programs based on Open ADR communication between the utility and customer devices. In addition to this requirement utilities in California are also providing incentives of $300 per kilowatt of demand that that is connected to demand response programs that can be reduced through automated controls such as automated building energy management systems.

Electric Chillers for Storage and Grid Regulation

Traditional chilled water storage systems have focused on utilizing cheap nighttime power to generate and store water or ice for use during the day. These systems have been successful in reducing system peak loads and reducing costs for many years. However these cooling systems have the potential to integrate with the electric grid in a similar way as the water heaters in the example above. They can also be utilized to provide demand response, balance renewable energy, and provide ancillary services. A recent study by Fraunhofer and MIT illustrated how chiller power demand could be modulated in a predictable and controllable way to provide grid regulation services similar to a conventional power plant.[144]

[vii] http://www.openadr.org/

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Box 1: Traditional Combined Heat-and-Power as a Continued Pillar of Transformed Power Systems

While utilzing CHP to improve system efficieny isn't new it does provide a key pathway to increase delivered energy productivity. In a typical coal- or gas-based power plant only 30%–40% of the energy content of the fuel is converted to electricity. For example, the average efficiency of utility generation in the United States has remained at 34% since the 1960s.[145] A large amount of the energy is lost in the form of heat. A combined heat and power plant is able to utilize previously wasted heat for productive purposes. Typical efficiencies range between 60% and 80%,[146] in comparison to 45%–50% efficiency of separately generated power and heat.[147] Because the plants are more efficient they need a smaller amount of fuel to supply the same amount of energy, thus reducing the pollution of every kWh generated and raising the economic output of every kWh generated, thereby increasing *delivered energy productivity*. Denmark has some of the world most efficient CHP plants for example, the Avedøre-2 power plant utilizes up to 95% of the input fuels' energy content.[148] A second way to increase delivered energy productivity from CHP is to utilize renewable resources to provide the fuel for the systems which further reduces the pollution of every kWh generated. Denmark is also a leader in this area and about half of the fuel for its CHP systems comes from renewable or waste sources.[149]

2.9 Integration with Transport

In the past, electric and transport systems were largely planned, designed and operated separately. As such, it was considered unnecessary for electricity planners to consider transport patterns or demand, other than municipal electric public transit such as subways and trolley buses. Further, it was also unnecessary for an urban transport planner or automaker to consider electric power systems, or incorporate power system integration into urban planning and vehicle designs.

In transforming power systems, the two formerly separate sectors are becoming increasingly connected through expanded deployment of hybrid and electric vehicles, and to a more limited extent through hydrogen fuel cell vehicles. Integrated transport and power infrastructure planning is supporting expansion of data-driven, intelligent systems that support flexibility, load balancing, and greater overall efficiency. This includes "smart city" planning and designs that integrate electricity and transport at an urban level as well as broader national or regional infrastructure planning to support integrated systems.

Innovation #1: Electric Vehicle Smart Charging for Flexible Demand

In areas of high renewable energy penetration, curtailment can be necessary during times of limited system flexibility and can lead to lost payments to renewable energy producers. In addition, during periods of high output from distributed energy sources, generation can substantially exceed local loads. In these circumstances, electric vehicle "smart charging" can allow for flexible storage of excess power, supporting a more intelligent and efficient power system.

Examples and evidence

Electric Vehicles Contribute to Wind Integration in Scotland

Orkney Isles, Scotland offers an innovative example of utilizing electric vehicles to absorb excess renewable energy rather than curtail output.[150] Orkney Isles occasionally generates more than 100% of electricity demand with renewable energy sources, largely through a number of small community-owned wind turbines. During times of peak wind energy supply, electric vehicles provide an option for turbine owners to absorb any excess power and avoid lost feed-in-tariff payments. Further, given that mainland Orkney Island is only 200 sq. miles, making most trips a short distance, electric vehicles are a particularly attractive mode of transportation. As Scotland recently announced plans to meet 100% of electricity demand with renewable energy by 2020, experience from Orkney Isles could inform national level efforts.[151]

Integrated Vehicle-To-Home Systems in the United States and Japan

In 2014, Honda, PG&E and the University of California-Davis partnered to pilot a "smart home" that incorporates a 10 kWh battery storage system to charge an electric vehicle, balance load associated with the home's electricity consumption, and improve reliability through demand response. In addition the project will assess viability of reused electric vehicle batteries for broader grid support applications.[152]

A Second Life for Used Electric Vehicle Batteries on Yume Shima Island, Japan

On Yume Shima Island, Japan, 4R Energy Corporation is exploring the power potential of used electric vehicle batteries through a grid energy storage pilot project with a solar power facility on the island. From 2014 to 2017, the pilot project will assess the potential of the storage facility, connecting multiple used electric vehicle batteries, to smooth energy fluctuations associated with variable solar power. Ultimately the project seeks to make the business case for this type of storage system.[153]

Deployment of Used Electric Vehicles to Support Flexible Demand in Hawaii

To expand the electric vehicle market and support flexible electricity demand, the Hawaiian Electric Company (HECO) launched a program to buy electric vehicles from rental car agencies and then sell them to consumers as used vehicles. In addition, HECO installed 20 quick electric vehicle charging stations and is supporting a broader electric vehicle eco-tourism program.[154]

Innovation #2: Real Time Data for Power Demand Intelligence

Vehicles have historically had very limited connection to internet and power networks. This is changing as cars become platforms for information technologies. The resulting proliferation of real time data is supporting interconnected and optimized transport and electricity systems. Traffic and battery status data can inform power demand predictions associated with electric vehicles, while pricing information can influence consumer decisions to support load balancing.

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Examples and evidence

Electric Vehicle Data for Urban Planning in Japan

Electric vehicles are also becoming an integral aspect of innovative urban planning models. In Tokyo City, Japan, the local government is collaborating with Toyota through an initiative called Harmonious Mobility (Ha:mo) launched in 2012. Ha:mo combines multiple modes of transportation and real time data to support highly efficient urban transport. The electric vehicle sharing aspect of the program leverages data on battery status, traffic, and likely times of arrival at charging stations to support a highly interconnected network. With this information, better predictions of power demand could enhance efficiency of grid operation.[155]

Real-time Data for Pricing and Load Balancing in Germany

Bringing together electric vehicles, intelligent systems, and flexible demand, in Munich, Germany consumers are being equipped with smart data to influence electric vehicle charging behavior and increase grid efficiency. With the use of a mobile app, electric vehicle owners can access real time pricing data, which ultimately allows them to benefit from lower prices, while also charging in a way that supports peak demand reduction and avoidance of greater GHG-emitting generation during high demand periods.[156]

Innovation #3: Coordinated Electric Vehicle Infrastructure and Grid Planning

Planning for electric vehicle infrastructure, principally charging stations, is a critical element to support scaled up deployment. Charging stations interconnected with electricity grids require robust planning and analytical effort to ensure efficient operation. Globally, slow charging stations doubled between 2012 and 2014, while fast charging stations increased eight-fold over the same period.[157] A number of countries and entities are undertaking such efforts and transforming traditional planning models to focus on energy system integration.

Examples and evidence

India's National Electric Mobility Mission Plan (NEMMP)

Under the NEMMP released in 2013, India aims to deploy 5 to 7 million electric and hybrid vehicles by 2020. To support this effort, and in partnership with the Clean Energy Ministerial Electric Vehicles Initiative, the Government of India performed an economic and environmental cost benefit analysis associated with the NEMMP target and performed detailed modeling of charging siting options to create an optimal distribution of electric vehicle charging stations in New Delhi.

Fast-Charging Networks in the United States

Building on a network of approximately 20,000 electric vehicle charging stations in the United States, in early 2015 BMW and Volkswagen launched a program to deploy 100 high-speed (approximately 20 minute) charging stations on various large highways in the United States by the end of 2015. The charging station initiative, operated by

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ChargePoint using a subscription-based model, moves beyond current efforts including Tesla's network of charging stations (exclusively for Tesla vehicles in California), as the stations will be compatible with most currently available electric vehicles. This innovation also moves beyond the initial idea that electric vehicle charging would primarily occur at residences (or within the vicinity) and recognizes consumer preference for freedom of mobility.[158]

Battery-swapping in China

As of 2012, China's State Grid, a government-owned entity that manages electric grid investments,[viii] had deployed 168 electric vehicle battery-swapping stations throughout China, making up approximately 85% of battery swap/recharge stations globally.[159] In Hangzhou, China, a large network of electric taxis uses battery swapping stations to exchange batteries throughout the day. Battery swapping generally takes about 10 minutes and batteries are recharged in approximately 2 hours. Vehicle design, workforce training, and efficient facility processes are all critical elements for success of this business model, which will likely continue to be most practical for vehicle fleet and public transport applications, rather than private vehicles. In addition to supporting non-disruptive, low emission public transport services, it has been proposed that batteries left at the charging stations could be used to support grid load balancing and power storage through flexible demand. Grid connection models are yet to be piloted, but do offer great potential to enhance intelligence and efficiency of electric systems.[160]

Innovation #4: Wind Power Produces Hydrogen-Fuel for Vehicles

During periods of excess supply, wind power can be used to generate hydrogen fuel that can be used as fuel for vehicles (as well as for stationary applications). Such integrated systems can more closely link power generation to transport through long-term storage. Early large-scale "concept" projects are now beginning to emerge to demonstrate this long-term option.

Examples and evidence

Wind-to-hydrogen Concept Project in Germany

The multinational corporation Linde Group plans to begin hydrogen production in a large-scale wind-to-hydrogen fuel facility in Mainz, Germany in 2015. The hydrogen can be used for both transportation and stationary power applications and the facility is planned to convert up to 6 MW of wind power to hydrogen, drawing from nearby wind farms.[161] Germany as well as a number of other countries (notably, Japan and United States/California) is investing significantly in hydrogen fueling stations with approximately 50 fueling stations planned or under construction.[162] Hydrogen costs have also decreased in recent years in line with required platinum input price decreases, making the technology more commercially viable. Private companies are planning the release of a number of hydrogen-powered vehicles in the coming years and, as noted,

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[viii] For additional information, visit www.sgcc.com.

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countries are investing in necessary fueling infrastructure.[163] Connecting hydrogen production with wind power could increase support for hydrogen vehicles as environmental considerations and climate change continue to influence consumer decisions.[164]

2.10 Storage

In the past, the only storage resources generally considered practical for bulk system balancing were hydro and pumped hydro. Pumped hydro was typically developed to arbitrage between night and day, and traditionally developed in combination with inflexible baseload plants. Power system design, operations, and markets have all evolved over the past several decades on the basis that new storage of electricity is not available or economically viable, and thus instantaneous supply must always equal (and follow) instantaneous demand.

In transforming power systems, the fundament tenet of power systems that supply must always equal (and follow) demand, is being replaced by the flexibility granted by energy storage technologies, as well as many demand-flexibility innovations (see Section 2.6). There are many emerging forms of storage that are allowing power systems to become more flexible and accommodate increasingly variable demand as well as variable renewable generation. Also, storage at the transmission, distribution, and end-user levels is beginning to provide clear economic and reliability value to transmission and distribution utilities and end-users.

Innovation #1. End-user (or "Behind-the-Meter") Storage is Now Used to Provide Economic Benefits to End-Users

At least two basic business models are emerging for end-user storage. First, batteries coupled with solar PV provide end-users the ability to "self-consume" more of their solar generation, rather than send it (sell it) into the power grid, providing economic benefits depending on policy and tariff conditions. Second, batteries can reduce (shave) the end-user's peak power demand and thus reduce "demand charges" (capacity charges) that are based on the customers' peak capacity over the day or month.

Examples and evidence

PV-Battery Installations to Maximize System Income in Germany

In Germany, many end-users, particularly residential and commercial customers, are installing batteries with solar PV systems. In the current German policy framework, this enables these customers to receive the equivalent of the avoided retail tariff for their solar power, rather than just the feed-in tariff rate. In 2014, the retail tariff had risen to more than twice the feed-in tariff rate, and was continuing to rise while the feed-in tariff rate was continuing to fall, providing a significant incentive to reduce grid purchases through self-consumption of solar power, rather than sell the solar power. The economics of this model were on the verge of covering the extra costs of adding battery storage through the

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increased revenue of self-consumption over grid-sales. For example, according to one solar leasing company in Germany, a typical battery installation might increase the share of solar generation that is self-consumed rather than sold to the grid from 33% (without battery) to 66% (with battery).[165]

Battery Storage to Increase Solar PV Revenue in Japan

In Japan a similar trend to that of Germany is appearing. Manufacturers, including Kyocera and Sharp, have started to actively promote solar PV combined with energy storage. A manager from Sharp recently predicted that "in a few years, the Japanese PV market will be shifted to the "self-consumption" mode, in which excess generated electricity will be stored (instead of being sold) due to declining FIT incentive rates and raising electricity prices […]." In recent years, some companies such as Panasonic have already been promoting solar PV and energy storage in Japan, but the selling point was the opportunity to use batteries to arbitrage time-of-use rates offered by some utilities such as Tokyo Electric Power Company. The idea behind this arbitrage strategy is to store energy during non-peak hours, when it is cheap, for use during peak periods, when it is more expensive.[166]

Large-scale Batteries for Peak Demand Savings by Gills Onions (Oxnard, California, United States)

Gills Onions faces a time-of-use tariff that assesses a demand charge based on maximum demand for the entire month. A short spike in power may fix the demand charge for the entire month. Gills Onions contracted with an energy storage provider to install, own, and operate a 600-kW/3.6-MWh "flow battery" to reduce peak demand, saving hundreds of thousands of dollars per year in operating expenses. The energy storage provider shares in the savings.[167] (See also Section 2.5 on markets and prices.)

Innovation #2. Storage Providing Economic Benefits to Transmission and Distribution Utilities

Storage is increasingly installed by utilities to forestall or avoid costly "wire investments" such as line and transformer upgrades, and also to reduce costs by shaving demand peaks. Traditionally, transmission and distribution utilities have had to invest in wires to meet increases in peak load, even if just for a fraction of the day. Now, utilities can invest in energy storage instead, to shave peak demand and avoid costly wire investments, especially transformer upgrades, in specific locations. This also creates a "locational value" for storage that depends on load, supply, and transmission and distribution wire capacity constraints for that specific location.

Examples and evidence

Regulatory Model to Value Storage in California

California began a new regulatory proceeding in 2014 called "Distributed Resource Planning," which requires utilities to identify those locations on their distribution grids where distributed resources, including storage and distributed renewable generation, can forestall distribution wire/transformer upgrades. This proceeding creates a "locational

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value" for storage that reflects its contribution to avoided distribution system investments.[168] (Also see Section 2.3 on distribution grids.)

Utility-Scale Batteries for Grid Balancing in Hawaii

In Hawaii, Kaua'i Island Utility Cooperative is significantly deploying solar PV and has opted for co-located utility-scale batteries to help balance the variability of some of its solar projects. The system also provides grid support for island-wide PV systems.[169]

Utility-Owned End-User Batteries in Auckland, New Zealand

The Auckland DSO Vector is installing end-user batteries with customer-side PV with the goal to reduce Vector's peak capacity charges that it must pay to the ISO, by "peak shaving" the total DSO load by remotely controlling the customer-side storage. Vector also believes that these batteries will ultimately reduce local network upgrade costs.[170]

Utility-Scale Storage to Improve Transmission Reliability in Presidio, Texas

Electric Transmission Texas has installed a 4-MW, 32-MWh sodium-sulfur battery in Presidio, Texas to reduce short-term outages for the city from an aging and declining-reliability 60-mile transmission line serving the city, before the line is replaced. The project was classified as a "necessary transmission upgrade" by ERCOT, the Texas ISO.[171]

Utility-Scale Storage for Grid Balancing in Tehachapi, California

Southern California Edison (SCE) is conducting the Tehachapi Energy Storage Project, which is one of the largest lithium-ion battery systems in the world, and will allow SCE to evaluate how storing and dispatching large amounts of energy may improve the flexibility and reliability of the next-generation grid.[172]

Innovation #3. Market Designs and Rules Created to Allow Third-Party Energy Storage Projects to be Commercially Profitable

Revisions to electricity market designs and rules related to energy storage are supporting power system transformation by allowing storage projects to better gain revenue, and become more profitable, from sales of stored power into wholesale markets, including real-time ancillary/balancing markets.

Examples and evidence

Performance-based payments in PJM wholesale markets (United States)

FERC Order 755 (2011) directs ISOs to implement a two-part payment for frequency regulation service, including a capacity payment and a payment for performance that reflects the quantity of frequency regulation service provided. Following this order, PJM changed its regulation market to reward faster resources able to respond more quickly and accurately. In response, AES Energy Storage then installed a 32-MW Lithium-ion battery on the site of an existing wind farm as "Flexible Operating Reserve Capacity." Over a two-year period 2011–2013, this battery provided over 400 GWh of regulation service to the PJM ancillary market, on a purely commercial basis, with no subsidies,

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made possible by the new tariff/market regime created by FERC Order 755 and PJM's implementation of that order.[173] (Also see Section 2.5 on markets and tariffs.)

Innovation #4. Storage Enabling "Virtual Power Plants"

"Virtual power plants" (VPPs) is a phrase more and more frequently used by some in speaking about power system transformation. The concept of a VPP is that it combines distributed generation with storage, and potentially demand response, to provide a constant-output power plant with less variability and more flexibility. Often, the different components of the power plant, including many disparate distributed generators, can be physically located in many different locations. These components are tied together through information and communication technologies to make them controllable as a single entity, as if it were all together in one place.

Examples and evidence

VPPs by German DSO EWE

Distribution utility EWE in Germany is developing VPPs as alternatives to further investment in the distribution grid. The idea is to reduce peak loading on distribution system wires and transformers, by allowing these virtual power plants to supply local loads, including the integration of demand-response and storage with existing solar and wind plants on EWE territory.[174]

VPPs Participating in California's Wholesale Market

The company Stem Distributed Storage is participating in the California wholesale market with aggregated behind-the-meter energy storage and real-time data analytics. Host customers for the energy storage devices include the InterContinental San Francisco and InterContinental Mark Hopkins hotels. With this technology Stem helps commercial and industrial businesses to more effectively manage energy expenses and by aggregating resources it can also quickly dispatch power to the grid when needed.[175]

Innovation #5. Storage in Physically Remote Locations Paired With Generation for Grid Stability and Reliability

In physically remote locations, storage paired with generation resources can offer greater grid stability, reliability, and lower generation costs. Storage can offer these benefits broadly even when not paired with generators, but the economic case for such pairing improves in remote locations.

Examples and evidence

Large-Scale Storage for a Coal Plant in Chile

A 20-MW/5-MWh lithium-ion battery was added to a 550-MW coal power plant in Mejillones, Chile, to provide reserve capacity and system stability, and allow additional generation (and revenue) from the plant to be delivered to customers rather than held

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back in reserve. Given the resource and tariff situation, the storage addition was commercially profitable.

Storage for Remote Alaska

Metlakatla Power and Light Company serves 1000 residents on an island in Alaska, and uses 1-MW storage to balance its hydro and diesel generators. Golden Valley Electric Association in Fairbanks Alaska uses a 27-MW/40-MW battery for emergency power.[176]

2.11 Microgrids

In the past, microgrids were quite rare, and cost and complexity limited them to very unique situations with extraordinary cost-benefit justifications.

In transforming power systems, microgrids are becoming more commonplace and justifiable due to rapid technology cost declines, power system pricing models that allow microgrids to better capture the benefits of distributed resources (including integration of heating and cooling), and the emergence of new retail pricing policy frameworks and business models that can turn microgrids into profitable energy service providers, not just technology solutions.

Microgrids are localized grids that may operate in grid connected or islanded mode. Microgrids may generator a high share, or even all, of their own power from local distributed resources and may operate in a more autonomous or more predictable manner to the bulk grid relative to the case where all the load were simply connected individually to the bulk grid. Microgrids are also designed to disconnect from the traditional grid to operate autonomously, which can help to mitigate grid disturbances and strengthen grid resilience.[177] Figure 13[178] illustrates several different potential scales of microgrids.

Navigant Research has identified at least 4.4 GW of total microgrid capacity throughout the world as of mid-2014, with North America being the leading market.[179] Microgrid utilization is growing rapidly and helping to support power system transformation by providing flexible distributed generation that can benefit customers and the power system in a number of innovative ways. (See also the innovations in Section 2.3 on distribution systems.)

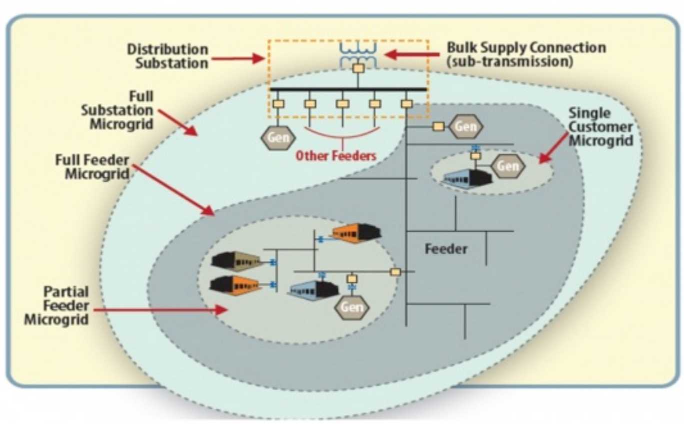

Figure 13. Illustrative microgrid configurations at different scales

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Innovation #1: Microgrids Providing Increased Customer Resiliency During Grid Outages

The distributed generation in a microgrid can be utilized to mitigate the impacts of large scale grid outage on the critical functions of the microgrid owner. Military installations, research laboratories, data centers, and banks often have backup power systems so that their operations are not impacted by commercial grid outages. Until recently many of these backup power systems were individual diesel generators that were utilized only during emergencies. However, advanced microgrids are now being designed in many cases to provide cost savings when the grid is available and resiliency when it is not.

Examples and evidence

Grid Resilience During Major Storms on the East Coast of the United States

Hurricane Sandy caused widespread environmental, property, and economic damage to the East Coast of the United States in 2012. However several key institutions such as Princeton College, Danbury Hospital, and the Co-op City housing community in Bronx County, New York were able to help mitigate the economic impact of the storm and recover faster thanks to CHP-powered microgrids.[180] Princeton University's microgrid is able to connect and disconnect from the utility, and supply heat and power to the campus with a 15 MW natural gas-fueled combustion turbine and a solar PV array.[181] During the widespread electrical outage following the hurricane, the microgrid provided all the energy for the campus and the campus became a refuge for the local community and first responders.[182] During normal conditions when the electrical grid is present, Princeton uses its microgrid to provide economic benefits. During the day the generation in the microgrid is utilized to reduce the peak energy load of the campus and at night it is utilized to cool and store chilled water. Because of the value and performance of these microgrids during hurricane Sandy, several states on the East Coast of the United States including New Jersey, New York, and Connecticut are actively developing and executing programs to encourage and fund microgrids designed to provide resilience for future storms.

Clearwater Mall Microgrid for Commercial Reliability in South Africa

Many commercial businesses in developing countries face unreliable local grid power and consequent daily economic disruptions. The Clearwater Mall near Johannesburg, South Africa is one such example, and typically faces one or two 4-hour outages per day.[183] Clearwater Mall has developed a novel solution. In cooperation with the company Echelon, the mall is deploying a microgrid, with smart meters, backup generation, and advanced monitoring to provide its more than 200 stores a unique solution for reliable power.[184] The system provides customers with individual meters to monitor actual energy consumption instead of the standard in South Africa where tenants would normally pay a fee per square foot. Also, tenants can opt into the microgrid system to provide backup power in the event of a grid outage. The current microgrid power system is diesel generators with the hope of integrating solar PV in the future. The Echelon system records real time usage during grid outages and bills retailers for actual power consumed. The Clearwater Mall microgrid illustrates an example of smart microgrid technology being utilized by businesses to overcome unreliable grid power. It also demonstrates an

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efficient cooperative solution for the entire mall rather than the alternative of each retailer needing an individual backup generation system.

United States Military Microgrids for Energy Security

In order to increase energy security at its installations the United States military has been developing and executing a number of microgrid projects. These microgrids are intended to provide power to critical military functions in the event of a commercial grid outage, natural disaster or terrorist attack. The Smart Power Infrastructure Demonstration for Energy Reliability (SPIDERS) microgrid program is installing microgrids at three installations (Pearl Harbor, Fort Carson, and Camp Smith) with increasing levels of capability and sophistication.[185] Novel features of the SPIDERS projects include integration of solar PV and plug in electric vehicles as well as utility demand response. Through the ESTCP Technology demonstration program the U.S. Department of Defense is also installing a number of advanced microgrids for energy security, one example project at Marine Corps Installation Miramar involves developing a 100% renewable powered microgrid utilizing solar PV and a flow battery for several buildings. Miramar is also developing a larger microgrid project that will serve approximately 100 buildings with a mix of conventional fossil fueled generation and renewable energy as well as provide economic savings through peak load reduction, demand response, and self-generation.

Innovation #2: Microgrids Providing Bulk-Grid Power System Services

Microgrids can be utilized to increase utility reliability and resiliency plus provide other system services. A large number of smaller distributed microgrid systems can reduce the impact of the failure of any single, microgrid, generation plant or transmission point on the overall system and can allow for more flexibility in system reconfiguration. The generation in a microgrid can be utilized as a resource in a power system to help avoid system outages and recover from them faster. Microgrids can also be utilized to provide other systems benefits such as peaking power, demand response, and ancillary services.

Examples and Evidence

University Microgrid Provides Grid Services, San Diego, California, United States

The University of California at San Diego has been developing one of the most advanced microgrids in the world over the last several years. The microgrid and associated generation provide 92% of the campuses electrical needs and save $8M per year compared to purchasing energy.[186] The main generation source is a natural gas cogeneration plant; however, the campus also contains a fuel cell, solar PV, and energy storage. In 2007 wild fires were causing grid disturbances for the local utility company, which asked large customers for support. UC San Diego reduced their energy consumption and increased their energy generation going from 3 MW of imported power to 4 MW of exported power in 10 minutes; this helped save the macro level grid from a large outage.[187] The campus is a leading provider of demand response and regularly curtails 6–10 MW of load in part through 4,000 controllable thermostats.[188] The campus also features many other innovations such as solar forecasting, plug-in vehicles, synchrophasors, and power system analytics. The UC San Diego microgrid is one example of an advanced microgrid that provides a number of grid-supporting services to the utility company as well as cost savings to the campus.

Microgrid Increases Customer Reliability Borrego Springs, California, United States

San Diego Gas & Electric (SDG&E) utility company operates a microgrid in the city of Borrego Springs. Borrego Springs is in a remote area with only a single sub transmission utility power line that runs over mountainous terrain that feeds the town. Historically the town has experienced a relatively high number of outages caused by weather and storms that impact the power line. In 2008 Borrego Springs began a microgrid demonstration project aimed principally at increasing reliability, reducing peak loads, and demonstrating microgrid technology.[189] The microgrid contains a mix of energy storage, diesel generation, and controls. The initial project successfully demonstrated the ability to island and power the town with the microgrid. The ability to isolate and self-generate vastly increased electric system reliability for the town. The project also demonstrated a customer demand response program to reduce loads based on price signals known as price driven load management. Under this program electronic price signals were sent to home area networks and customers were encouraged to reduce loads on pool pumps, thermostats, and electric vehicles.[190] Recently SDG&E was awarded another $5 million grant for the project to improve and expand the microgrid. A key component of this next phase will be to incorporate a privately owned 26 MW solar PV array into the microgrid, making it one of the largest microgrids in the country capable of being fully powered by renewable energy.[191]

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3 Towards Indicators of Power System Transformation

The many innovations described in Chapter 2 provide evidence that power system transformation consists of diverse innovations across an ecosystem of interrelated domains. This chapter goes a step further to propose a framework of indicators that would allow for measurement of power system transformation.

Our proposed framework builds upon and complements valuable prior work, including Cochran *et al.* 2012; the IEA "Grid Integration of Variable Renewables" (GIVAR) reports; the World Bank "Readiness for Investment in Sustainable Energy" (RISE) Indicators; Sustainable Energy for All "Global Tracking Framework; and the IRENA "Renewables Readiness" project, among others.[192]

Our framework is unique, however, in that no comprehensive alternative yet exists at a level detailed enough to measure year-by-year progress and status in the way this report has portrayed power system transformation. With our framework, we hope to stimulate the global dialogue on how to measure progress in power system transformation. The key questions addressed in this chapter are:

- What indicators might reasonably show progress towards implementation of power system transformation?
- What framework might allow those indicators to be organized and understood?

The indicators and the associated organizing framework we suggest are not intended to be prescriptive or exhaustive; rather, we view them as a modest first step toward formulating a more comprehensive approach to measurement. While this section does not document country experiences or attempt to compare nations to each other, it is likely that both activities will be increasingly valuable in coming years. A robust set of indicators might allow policymakers to "take stock" on the current status of their transformation and conceptualize potential options for further exploration. A global survey might also allow policymakers to benchmark their progress with neighboring countries, regions, and the international community at large. Toward that end, we propose this preliminary set of indicators to initiate global dialogue in the coming years.

We expect that this framework might also be employed by CEM initiatives and their partners to perform a country-level global review of progress in power system transformation. The CEM initiatives aim to drive collaboration at the level of implementation—the specific actions and frameworks that policymakers, regulators, utilities, and other stakeholders will be grappling with in the years and decades to come. This indicator framework, as it evolves, can lead to more organized and systematic approaches for decision makers, in terms of understanding strategies, and measuring the results of those strategies, for long-term power system transformation.

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An Implementation-Based Framework for Transformation Indicators

Based on the innovations and examples in Chapter 2, five broad types of implementation-based indicators clearly emerge. When assessing progress towards implementation of power system transformation, we propose:

A. Wholesale Market Design and Bulk System Operation
B. Retail Market Design and Distribution System Operation
C. Planning
D. Technology
E. Cross-Sectoral Integration.

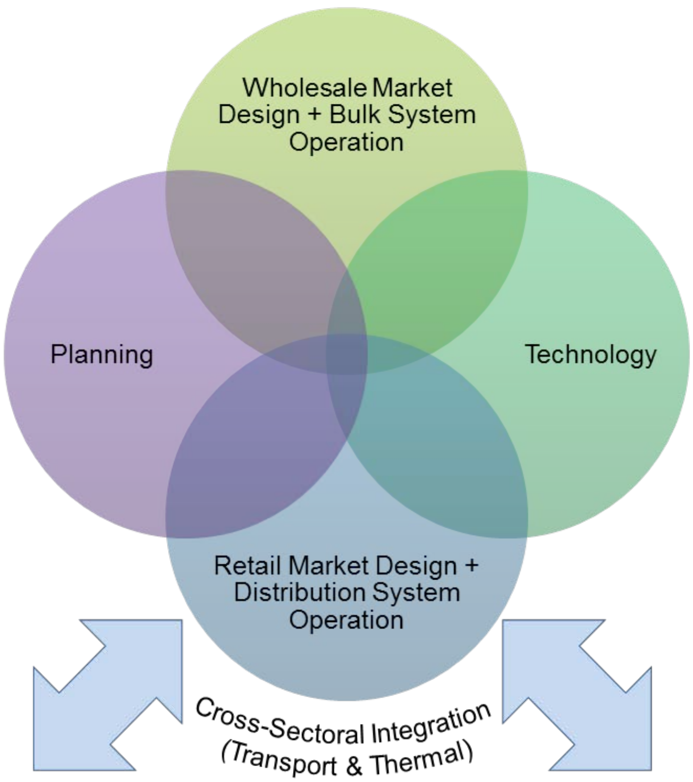

Figure 14. Five suggested categories of indicators of power system transformation

For each innovation, progress can be approximated by the degree of emergence, mainstreaming, and effective impact of these innovations in a particular power system jurisdiction (see Box 2). These degrees of emergence can be measured in three ways:

- **The degree to which the innovation is 'in place' in a jurisdiction** (e.g., Do customers have the option for time-of-use rates?). For various indicators below, 'in place' could be either "present," "emerging," "planned," "piloted on a limited scale," "not present," or "not applicable."

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- **Quantifying the level of participation in the innovation** (e.g., How many customers are enrolled in the time-of-use rate), and
- **Quantifying the effective impact of the innovation** (e.g., What are the public benefits and power system impacts of the given level of time-of-use participation).

Combining these three ways of measuring innovations, our indicators thus attempt to lead back to the question of enhancing public welfare.

Box 2: "Power System Jurisdiction" Boundaries

A "power system jurisdiction" can be defined in several ways, and multiple boundary definitions may be allowed with regard to indicators. The most obvious jurisdiction is the entire power system associated with a single TSO. But for some indicators, the jurisdiction would likely be the DSO or the power system associated with a specific utility company at the distribution level. Or a jurisdiction might be a collection of TSOs entwined in a common market (such as in the EU). Finally, a jurisdiction might be based on the actions of a specific regulatory authority that cuts across multiple TSOs or DSOs or other entities.

It will likely be difficult to maintain a common definition of power system jurisdiction across all countries. Take for example a possible indicator-driven statement: "Of all DSOs in the world, over half register "yes" for Indicator X." This raises the issue of how to aggregate indicators over multiple jurisdictions. If not globally, then over what subset of jurisdictions would it make sense to try to aggregate indicators? One could say "Over all TSOs in Europe" as there is a common framework for a "TSO jurisdiction" but not necessarily a framework that would apply directly outside of Europe.

Under each of the 5 indicator categories, we suggest 10 specific implementation-based indicators (labeled A-1, A-2, B-1, B-2, C-1, D-1, D-2, D-3, E-1, E-2.). These indicators are conceived of as variations of the question "to what degree…?" The answers to these questions could be quantitative or qualitative, and the authors leave to readers and future editions further refinement. In the framework here, the measurement of the indicators is based on some combination or subset of relevant innovations from Chapter 2.

A. Wholesale Market Design and Bulk Power Grid Operation

A-1. Wholesale Market Design

To what degree are innovative wholesale design elements present in the power system to incentivize desired characteristics and behavior?

- New market and financing mechanisms to unlock new sources of investment (see 2.5 Innovation #1)
- Frameworks for prioritizing investment in system resources (see 2.5 Innovation #2)
- Wholesale energy market reform to unlock system behaviors (see 2.5 Innovation #4)
- Market frameworks for ramping capacity (see 2.5 Innovation #5)
- Market frameworks that allow zero or negative price to efficiently provide renewable energy curtailment signals (see 2.5 Innovation #6)

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- Allowing dynamic load (demand response) to bid into wholesale markets (see 2.6 Innovation #2)
- Market frameworks that create incentives to retrofit conventional generation for more flexibility (see 2.7 Innovations #1 & #2)
- Market designs and rules created to allow third-party energy storage projects to be commercially profitable (see 2.10 Innovation #3)

A-2. Bulk Power System Operation

To what degree are innovative transmission and grid operational strategies being employed in the power system?

- Integrating forecasting into transmission operations (see 2.2 Innovation #4)
- Transmission operation with real-time system intelligence (see 2.2 Innovation #5)
- Coordinating scheduling and dispatch across balancing areas (see 2.2 Innovation #6)
- TSO/DSO interface reliability coordination (see 2.4 Innovation #3)
- Wholesale energy market reform to unlock system behaviors (i.e., sub-hourly dispatch in TSO operation) (see 2.5 Innovation #4)
- Variable generation serves as a dispatchable resource (see 2.7 Innovation #3)
- Microgrids providing bulk-grid power system services (see 2.11 Innovation #2)

B. Retail Markets, Distribution System and Demand Side Operations

B-1. Retail Market Design

To what degree is innovative retail market design present in the power system to incentivize desired behavior?

- Local energy markets (see 2.3 Innovation #5)
- Customer pricing reform to unlock system behaviors (see 2.5 Innovation #3)
- Decoupling revenue from electricity sales (see 2.5 Innovation #7)
- Time-of-use pricing to increase demand responsiveness to power system needs (see 2.6 Innovation #4)
- Variable renewable generation serves as a dispatchable resource (see 2.7 Innovation #3)

B-2. Distribution System and Demand Side Operations

To what degree are innovative distribution-level and/or demand-side operational strategies being employed to manage distribution networks?

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- Advanced modeling of distribution systems (see 2.3 Innovation #2)
- Wind and solar energy forecasting for distribution system operations (2.3 Innovation #6)
- DSO actions to self-supply reliability services or to provide reliability services to the TSO (see 2.4 Innovation #1)
- TSO-DSO boundary reliability coordination (see 2.4 Innovation #3)
- Demand-response to support reliability within distribution systems (see 2.6 Innovation #3)
- Integrated Demand-Side Management (see 2.6 Innovation #6)
- Conservation voltage reduction (see 2.6 Innovation #7)
- Grid services from variable renewable energy plants (see 2.7 Innovation #4)
- Utilizing microgrids to support the larger power system (see 2.11 Innovation #3)

C. Planning

C-1. Integrated Planning Frameworks

To what degree do planning frameworks account for the variety and interplay of power system trends? Do planning frameworks anticipate interplay between bulk-system, distributed, and demand-side resources that will exist in the future? Do planning frameworks adequately address both reliability and flexibility? Do planning frameworks explicitly account for resource conservation and emissions reductions?

- Integrated resource and low emission planning approaches with innovative cross-sectoral linkages and impacts (see 2.1 Innovation #1)
- Water impact assessment required in IRP (see 2.1 Innovation #1)
- Interregional and international planning, and balancing area expansion (see 2.2 Innovation #1)
- Transmission planning for concentrated areas of variable renewable energy (see 2.2 Innovation #2)
- Including transmission considerations into interconnection processes (see 2.2 Innovation #3)
- Distribution system planning processes to better manage distributed energy resources (see 2.3 Innovation #1)
- Incorporating dynamic and static load into planning (see 2.6 Innovation #1)
- Coordinated electric vehicle infrastructure and grid planning (see 2.9 Innovation #3)

D. Technology

D-1. Smart Technologies

To what degree are smart grid technologies being deployed and serving as the foundation for the innovations discussed in this report?

- Advanced instrumentation and control of transmission and distribution systems (see 2.3 Innovation #3)
- Smart inverters and wind turbines providing network services (see 2.3 Innovation #4)
- Smart equipment codes and standards (see 2.6 Innovation #5)
- Advanced grid code requirements for new variable renewable energy generation (see 2.7 Innovation #4)

D-2. Flexible Resources

To what degree are new highly flexible technologies and strategies —such as demand response, storage, fast-ramping conventional generators, and controllable variable renewable energy generators—being adopted within power system generation mixes?

- Aggregate installed/contracted capacity of demand response (see 2.6 Innovation #1)
- Flexibility from Coal Plants (see 2.7.1 Innovation #1)
- Flexibility from Non-Coal Plants (see 2.7 Innovation #2)
- Grid Services from variable renewable energy generation (see 2.7 Innovation #4)
- Advanced grid code requirements for new variable renewable energy generation (see 2.7 Innovation #4)
- Aggregate installed capacity storage capacity (battery, thermal, or other) to provide system flexibility (see 2.10 Innovations #1 and #2)
- Storage for economic benefits to transmission and distribution utilities (see 2.10 Innovation #2)
- Storage enabling "virtual power plants" (see 2.10 Innovation #4)
- Storage in physically remote locations paired with generation for grid stability and reliability (see 2.10 Innovation #5)
- Microgrids providing increased customer resiliency during grid outages (see 2.11 Innovation #1)

D-3. Resource Efficient Technologies

To what degree are new resource-saving and emissions-reducing technologies being adopted within power systems?

- Water-saving technology deployment (see 2.1 Innovation #2)

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E. Cross-Sectoral Integration

E-1. Transport Sector

To what degree are electric vehicles (both charging and potential dynamic contribution to grid flexibility) explicitly included in market designs, planning frameworks, and operations?

- Managed electric vehicle charging for flexible demand (see 2.9 Innovation #1)
- Real time electric vehicle data for power demand intelligence (see 2.9 Innovation #2)
- Renewable energy production of fuel (e.g., hydrogen) for vehicles (see 2.8 Innovation #4)

E-2. Thermal and Buildings Sectors

To what degree are heating and cooling loads and thermal storage mediums being incorporated within power system markets, planning, and operations?

- Thermal loads and storage for system flexibility (see 2.8 Innovation #1)

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4 Spotlight Topic: Challenges and Emerging Roles for Regulators

In transforming power systems, new challenges and new roles are emerging for regulators. Regulatory authorities involved in the power sector exert a wide range of influences over power system planning, design, operation, investment, tariffs, and markets, as well as over the specific companies involved and the overall structure of the industry. These influences vary greatly in scope and approach depending on jurisdiction, state of power-sector development and structure, history, policy goals, resources, and other factors. Some of the specific issues raised by increasing amounts of variable renewable energy are detailed in previous 21st Century Power Partnership reports.[193]

Power system regulation is generally classified as economic regulation, which focuses on prices, quality, safety, and market rules (i.e., related to entry, exit, and investment). However, a degree of social regulation occurs when policy seeks to include social and environmental goals such as emissions reductions, energy security (autonomy), or subsidized service to specific classes of consumers.

Power system regulation is conducted by a variety of entities depending on jurisdiction, such as energy ministries or ministerial agencies, independent regulatory commissions, independent advisory agencies, and economic authorities entrusted with ensuring economic competition or development.

Power system regulation has traditionally been justified by several goals, including:

1. Enforcing the obligation to serve all customers and all demand (which in many jurisdictions represents a long-standing "social contract")
2. Maintaining reliability standards and oversight ("keeping the lights on")
3. Limiting the market power of monopolies or oligopolies that exist due to the natural-monopoly nature of "wire" elements of a power system (transmission and distribution), where competition would involve gross inefficiency from having to run multiple sets of physical wires
4. De-politicizing the price-setting process by entrusting it to independent regulatory bodies.

Historically, when power systems have been fully vertically integrated (combining generation, transmission, and distribution under one entity), regulation occurred primarily on the basis of controlling prices and ensuring reliability and the obligation to serve. This model is also called cost-of-service regulation. This model of regulation also tended to include requirements that sufficient long-term planning was conducted by the vertically integrated utilities to ensure that generation capacity would continue to meet the obligation to serve, given the long lead-times (often 5–10 years) of many power system investments. However, since there were no markets and no competition, no wholesale or retail market regulation was required, and most regulation focused on price setting. And,

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of course, regulatory approaches differ depending on what mix of public and private entities are being regulated.

Starting in the 1990s, as power systems around the world have undergone restructuring (also sometimes called liberalization) and unbundling to create competition in both generation and retailing, the role of the regulator has become vastly more complex. The current phase of power system transformation promises to add further complexity.

As introduced in Chapter 1, this report has been concerned broadly with power sector transitions to more sustainable energy models. The current transition amplifies a classic policy and regulatory "dilemma"—the relative role of market forces and policy mandates. Across the domains of planning, investing in, and operating power systems of the future, what should be the relative role of market mechanisms and of central control, e.g., mandates, targets, and standards? While a full examination of this dilemma in all contexts is beyond the scope of this report, general regulatory challenges are presented below, focusing on contexts where market forces currently play a decisive role in power systems.

In situations where unbundling and/or restructuring have led to market-based frameworks, the role of the regulator is already complex due to inherent features of electricity markets. Electricity markets are complicated because they must not only balance supply and demand on a conventional economic basis (price and quantity), but must simultaneously balance in three other ways:

1. On a minute-by-minute physical basis due to the underlying physics of electric power and the technical characteristics of generation technology
2. On a geographical (locational) basis due to transmission capacity constraints and the specific geography of generation resources and demand centers
3. On a contingency basis in terms of always ensuring power system reliability and integrity, while satisfying the various constraints on market-provided resources needed to achieve those goals.

Since the 1990s, in addition to regulation focused on the core needs of unbundling and market creation, power system regulation in many jurisdictions has also had to address several key areas:

- Long-term forecasting and investment planning to meet the obligation to serve. Such planning becomes more complicated to regulate in a restructured market, especially insofar as the planning has to be conducted by separate but interacting generation, transmission, and distribution entities. Market mechanisms and incentives are needed to create the necessary market conditions and price signals for adequate planning.
- The continued oligopoly market power of unbundled entities subject to competitive markets. There are many examples of inefficiencies, unmet policy goals, and even crises stemming from oligopolies in generation and conflicts of interest in terms of transmission access due to incomplete or poorly designed unbundling.

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- Renewable energy policies and mandates, such as feed-in tariffs, renewable portfolio standards (quotas) or targets, mandated competitive bidding of renewable energy capacity, net metering of distributed renewables at the customer level, rebates and investment incentives, and interconnection rules for new renewable generators.
- Energy efficiency policies such as demand-side management, investment incentives, time-of-use rates, and dynamic and seasonal pricing. Also investments in smart meters for end-users and the tariff regimes that go along with such meters.
- Customer self-generation policies governing on-site generation (i.e., gas turbines and combined-heat-and-power plants), and governing the conditions and prices under which such self-generation can be sold or exported back to the grid.
- Inter-regional market designs and rules and tariffs governing transfers between different power systems (i.e., transfers between different TSOs or across national boundaries).
- Handling the disposition or compensation of stranded assets that arise from restructuring. This includes generation assets that are no longer profitable under the new market structure.
- Emissions-reduction frameworks, including standards, quotas, cap-and-trade, and market-based or incentive-based frameworks.

The current status of power system transformation, as seen through the innovations and examples highlighted in Chapter 2, along with the indicator framework in Chapter 3, is increasingly accompanied by a number of additional challenges and potential roles for regulators. Some of these challenges are the result of anticipating and adapting to fast-paced technology change, while others are more the result of more fundamental changes in power systems that are occurring today, which require new ways of thinking and planning.

For example, flexibility becomes a dominant theme in transforming power systems. The basic regulatory and policy challenge is to provide necessary market, incentive, and/or mandate-based regulation to ensure that power systems of the future meet given reliability standards at the least possible cost, given future levels of variable renewable energy generation, more flexibility in power demand, energy storage, and the plethora of new technical and operational opportunities to use smart-grid technologies. This requires regulators to understand what types and levels of flexibility are required, what generation and demand-side resources can provide flexibility, and how to model and plan for, or create market structures and rules for, least-cost configurations of required flexibility. The need for flexibility is accompanied by a large number of regulatory challenges, such as:

- New methods of long-term power system planning that take into account much higher shares of variable renewables, much greater flexibility of customer demand, geographical conditions and constraints of renewable energy development, and new sources of power demand like electric-vehicle charging.

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- Employing energy-only markets with or without capacity markets for flexibility. As conventional generation is used more flexibly (see Section 2.7), the annual revenue from a given power plant can decline as the plant operates fewer hours at full load. A regulatory debate is how to ensure adequate capacity remains in the system even as the revenue from energy sales of conventional plants declines. One solution being pursued or explored in many jurisdictions is capacity markets, although there is still much debate about whether properly designed energy-markets can function with the need for capacity markets.
- Alternate formulations of reliability standards more suited to flexible power systems of the future, and/or joint reliability planning among multiple entities, such as among a group of TSOs. The ENTSO-E joint reliability planning framework in Europe is a good example.
- Regulation for incorporating energy storage into power systems at both local and aggregate levels. Part of the challenge is simply how to classify storage for purposes of regulation, interconnection, and tariffs—is it “load”, or a “generator”, or both, or neither?

Also, as seen in Section 2.3, the planning and operation of distribution-level power systems is undergoing fundamental changes, bringing new forms of localized energy markets, new approaches to distribution-system investment planning, new ways of thinking about the contribution of distribution systems to bulk-grid services like reliability and flexibility, and new frameworks for allocating the added costs of investment in distribution systems required for two-way power flows from higher levels of distributed generation, and incorporation of other smart-grid technologies.[194] Two examples of specific regulatory challenges at the distribution level:

- Regulation for incorporating smart-inverters into distribution systems at the local level, which requires new standards and practices and new ways of defining “grid services” and incorporating the value of these services into economic calculations through market mechanisms or incentives.
- Regulating the development of micro-grids and a variety of flexible-demand technologies and their integration into distribution systems, including technical standards, tariffs, costs and prices of “grid services” supplied or demanded.

And finally, some regulators are taking more pro-active roles in leading power system transformation. Such a leading role might mean envisioning a pathway of power system transformation and creating consensus among policymakers, utilities, stakeholders, and the public on this pathway, in time to manage the necessary transitions with the least amount of disruption. Thus such a leading role typically includes facilitating stakeholder dialogues involving the power industry, consumers, and technology providers or developers, to envision and build a consensus on how to advance. Such stakeholder dialogues are increasingly common in more and more regulatory jurisdictions, commensurate with the enormous regulatory challenges facing power system transformation.

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Many examples of existing planning, operating, and technology innovations in the above categories have been provided in Chapter 2 of this report. It is not the role of this chapter to exhaustively cover the entire history and all considerations involved in power system regulation. Rather, this chapter points out that, with power system transformation, the role of the regulator is also being transformed and becoming much more complex.

Thus the "status" of power system transformation globally must also include the status of how various regulatory authorities are managing to cope with the imperatives and opportunities of the various transitions and transformations. Future editions of this report will consider ways to report on the status of regulatory authorities' abilities and attempts to manage and lead power system transformation.

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5 Conclusion: Pathways Forward

From the landscape of innovations and evidence presented in this report, it is clear that pathways toward power system transformation are beginning to take shape. The complex set of forces and trends presents both challenges and opportunities, necessitating not only new conceptualizations of how power systems might function, but new approaches to spur innovation and amplify public benefits. Fostering a global dialogue about the scope and nature of power system innovation can support the development of effective policy visions and robust implementation frameworks.

Just as power systems are a convergence of technical systems, institutions and society, so is the landscape of innovation. Exploring the relations and tensions between these domains can clarify how policymakers might harness innovations in positive ways. A durable set of progress indicators can also allow policymakers to take stock on the current status of their transformation, contextualize the state of their national progress, and illuminate options for further exploration.

The codification of innovations presented in this report is a first step toward empowering policymakers in this realm, and can be used to focus efforts and facilitate dialogue among power system stakeholders. The indicator framework suggested in Chapter 3, as it evolves, may lead to more organized and systematic approaches for decision makers, in terms of identifying high-value transformation pathways and associated implementation approaches, and for measuring the results of employed strategies, toward promoting sustainable long-term power system transformations.

Beyond the present edition of this report, the path forward leads to a more collaborative international dialogue to describe, measure, and track the status and progress of power system transformation around the world. The 21st Century Power Partnership, in cooperation with global collaborators and leaders, provides a solid foundation for the next steps, which could include:

1. A global network of contributors to provide additional examples and evidence of the innovations presented in this report;
2. A thought-leaders group to deepen the descriptions of innovations presented in this report and document good practices with their application, and to refine the concept of power system transformation indicators;
3. Further refinement and focused applications of the indicators suggested in Chapter 3 to specific countries, regions, and/or types of power system jurisdictions;
4. International qualitative and quantitative tracking of specific indicators, in terms of the extent to which they are emerging around the world and the depth of impacts achieved;
5. Comprehensive sharing of policy-making experience and knowledge in implementation of key innovations toward power system transformation,

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potentially coupled with power sector transformation capacity building and technical assistance initiatives; and

6. Formulation of power system transformation vision statements by stakeholder networks including policymakers, customer groups, regulators, technology providers, and utilities.

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