ELECTRIC POWER RESEARCH INSTITUTE

Electric Power System Flexibility

CHALLENGES AND OPPORTUNITIES

POWER SYSTEM TRANSFORMATION

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INTRODUCTION

EPRI and its advisory members examined changes related to natural gas prices, load growth, energy policy, and the penetration of variable generation, and determined that the power system needs to transform to become more resilient, flexible, and connected [1]. This document addresses the power system's flexibility, a key driver of which is the rapid and diverse deployment of variable generation such as wind and solar. Variable generation combined with future uncertainty in fuel prices (primarily natural gas) for power generation drives power plant economics, the generation mix, and the order and frequency of plant dispatch.

Also driving the need for greater power system flexibility is the shift of customers to active energy users, and their expanding technology options such as solar photovoltaics panels, plug-in electric vehicles, smart appliances, and on-site energy management systems. Environmental regulations will have significant effects on the portfolio of grid technologies and the operation of power generation and delivery systems.

The transition to a more flexible power system requires a new portfolio of technologies and methodologies. This paper describes technologies and tools that EPRI and electricity sector stakeholders are developing and applying to address the challenge of power system flexibility.

Challenges, Current Research and Research Gaps

This paper examines the challenges and opportunities that are driving changes to the power system and the system's research and development needs. These will span power generation, the power delivery system, power system operations and planning, and consumers, while addressing environmental impacts.

The paper summarizes current research and points to research gaps and opportunities, from which EPRI will develop R&D roadmaps and action plans with utilities, industry suppliers, government agencies and non-governmental organizations, research entities worldwide, universities, technology providers, and other stakeholders. As this work continues, additional research opportunities will emerge based on continuing change in technology, business, and policy.

Variable Generation Drives Fundamental Change

Rapid growth in variable generation is driving the need for a more flexible power system and for a research and development strategy to help achieve that.

FLEXIBILITY DEFINED

Power system flexibility is the ability to adapt to dynamic and changing conditions, for example, balancing supply and demand by the hour or minute, or deploying new generation and transmission resources over a period of years. Primary challenges to be addressed near term include the rapid deployment of variable generation, fuel price fluctuations and uncertainty, changes to system standards and policies, and consumer adoption of new technologies such as energy efficiency systems.

The Immediate Need for Flexibility: A Brief Case Study

The immediate need for flexibility is made clear when power systems experience relatively rare conditions. In the United States for example, the California Independent System Operator (ISO) issued a “flex alert” in February 2014 encouraging residents to minimize electricity usage—a step typically taken in the height of summer heat waves. In this case, the measure was needed due to a confluence of events. After closing the San Onofre Nuclear Power Plant in 2013, California utilities became more dependent on natural gas-fired power plants. A nationwide cold wave drove up consumer use of natural gas for heating, reducing gas supplies available to Southern California utilities. Such events illustrate the end-to-end nature of challenges that the industry faces (from a closed nuclear plant to increased customer consumption of gas) and the interrelated electricity and gas supply and delivery systems [2].

FACTORS DRIVING THE REQUIREMENT FOR POWER SYSTEM FLEXIBILITY

Growth in Variable Generation

Motivated by decreasing capital costs and incentives, consumers, energy suppliers, and developers increasingly are adopting variable generation (for example, solar PV and wind) to supplement grid-provided electricity. Photovoltaics (PV) power generation has increased from approximately 4 GW of global installed capacity in 2003 to nearly 128 GW in 2013. By the end of 2013, U.S. PV installations grew to nearly 10 GW. Although parts of the U.S. have higher regional penetration of PV, this 10 GW represents less than 2% of total installed U.S. generation capacity. The variability, uncertainty, and asynchronism of these resources present implications for reliable power system operation and utilities need to factor these aspects of PV into planning and coordinating system modifications to avoid adverse outcomes.

Wind power is growing rapidly and some U.S. balancing areas meet more than one-half of load with wind power during some periods [3]. In some U.S regions for some customers, low-cost, flexible, natural gas generation has combined to make these options effectively competitive with retail electricity service.

In most cases, variable generation is connected to the grid, benefitting from its electrical support, flexibility, and reliability, but not integrated with the grid's operation. Consequently, the full value of variable generation is not realized with respect to providing support for grid reliability, voltage, frequency, and reactive power.

Variable generation, such as PV and wind, can produce energy at a low marginal cost due to subsidies and the absence of fuel costs. Additionally, thermal units may be dispatched less or not at all, reducing their revenues. Subsidizing variable generation (or more specifically, renewable generation) can reduce prices artificially in some cases, which further reduces thermal plants' revenues. These two effects can impair the economic viability of some thermal units, and may prompt owners to retire marginal units. Any resulting uncertainty in the generation mix calls for flexibility in response. A recent Wärtsilä study indicated that "several

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EU [European Union] states have identified a concern that the market may bring forward insufficient capacity under current market arrangements as a result of plant closures and the lack of investment in new capacity." [4]

A Pöyry study examining power markets in North West Europe predicted that wholesale power prices are likely to be increasingly dominated by effects of short-term weather patterns on solar and wind generation, increasing wholesale power market volatility and the unpredictability of wholesale power prices. The study pointed to periods of high prices when renewable output is low and to low prices during periods of renewable surplus. Such volatility and uncertainty drive the need for flexibility to accommodate these impacts [5].

Fluctuating Fuel Prices

Fluctuating fuel prices also drive the need for flexibility. U.S. natural gas prices have historically been more volatile than coal prices. From 2002 to 2012 the price of natural gas for power generation ranged from approximately $3.50/MMBtu to $9.00/MMBtu. Shale gas production has resulted in a price that is both low and nearly independent of geography. Figure 1 shows the effect of natural gas supply and price on power generation for 2003 and 2013. In April 2012 coal and natural gas fueled the same share of total generation of electricity for the first time since the U.S. Energy Information Administration (EIA) began computing monthly energy statistics [6]. Since that milestone, coal's share has increased. Given low natural gas prices, U.S. natural gas-fired plants may now dispatch ahead of coal, and in some cases, nuclear plants. Elsewhere in the world, the opposite is true.

The future price of natural gas is highly uncertain. EIA's projected 2040 natural gas prices under three scenarios range from approximately $8.50/MMBtu to approximately $17.50/MMBtu [7]. Such uncertainty is likely to continue to affect the generation mix, dispatch order, and frequency of various types of power generation, requiring flexibility to accommodate.

Consumers Choose New Technologies and Take on a New Role

Consumers will drive increased power system flexibility as they shift from passive buyers to active users, and as they install solar PV panels, and purchase plug-in electric vehicles, appliances, and equipment that enable them to

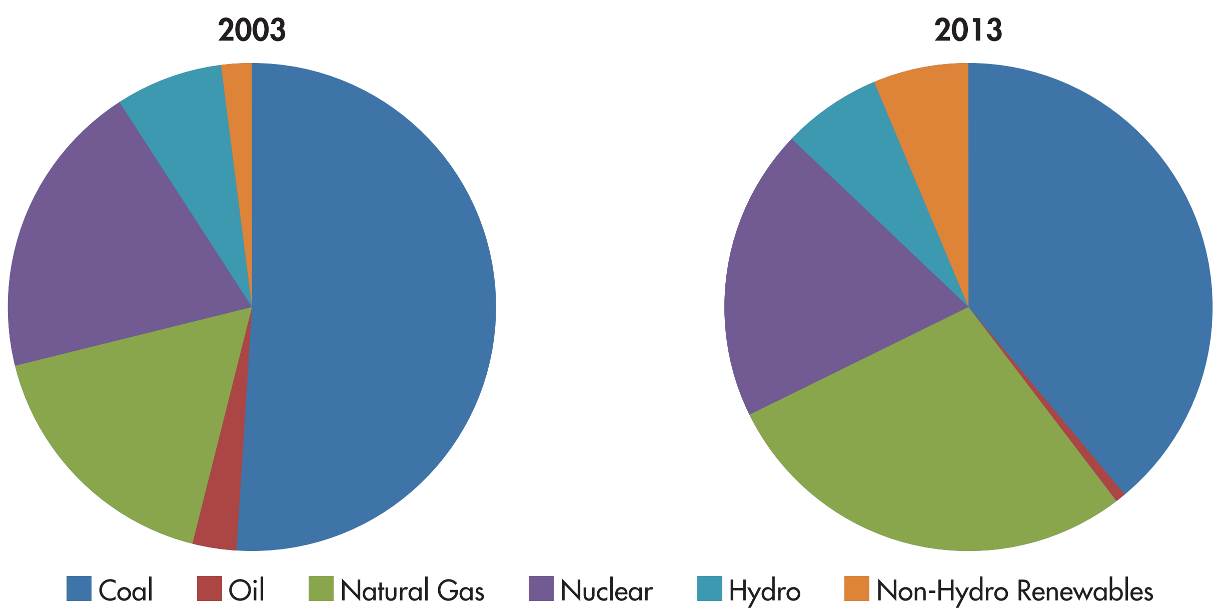

Figure 1. Share of electricity generated from various fuel sources in 2003 and 2013, showing the significant increase in natural gas generation and decrease in coal generation [6].

better manage electricity use. The aggregate effects of more active consumers is more variable load, requiring a flexible system to respond.

The drive towards low- and zero-net energy buildings using PV can reduce load but can also lead to local concentrations of highly variable load when local load does not correspond to local generation (for example, when PV output is reduced due to cloud cover). This can also lead to sharper peak demand (i.e., decreased load factor) and a more variable customer load shape as traditional loads (for example, HVAC and lighting) are replaced by "behavioral loads" (for example, plug-in electric vehicles and consumer computing).

These trends call for increased flexibility in two areas. First, increased local flexibility is needed at the distribution and generation level. Second, utilities need organizational flexibility due to changing customer expectations of utility services. These expectations include increased flexibility/ choice; increased availability of information, connectivity, and control at shorter time scales; and additional services such as PV.

Environmental Regulations and Policy

In the U.S., 29 states, the District of Columbia, and three territories have established renewable portfolio standards (RPS) for renewable energy production (see Figure 2) [8]. Further encouraging renewables are policies such as net metering, public benefit funds, property assessments, property tax incentives, rebates, grants, loans, sales tax incentives, and tax credits.

Environmental rules also drive the need for increased flexibility. U.S. environmental laws that impact power generation, transmission and distribution are the Clean Air Act, the Clean Water Act, the Resource Conservation and Recovery Act, and the Endangered Species Act. In the European Union, continental standards are established that the member states must meet. Also, stakeholder demands for

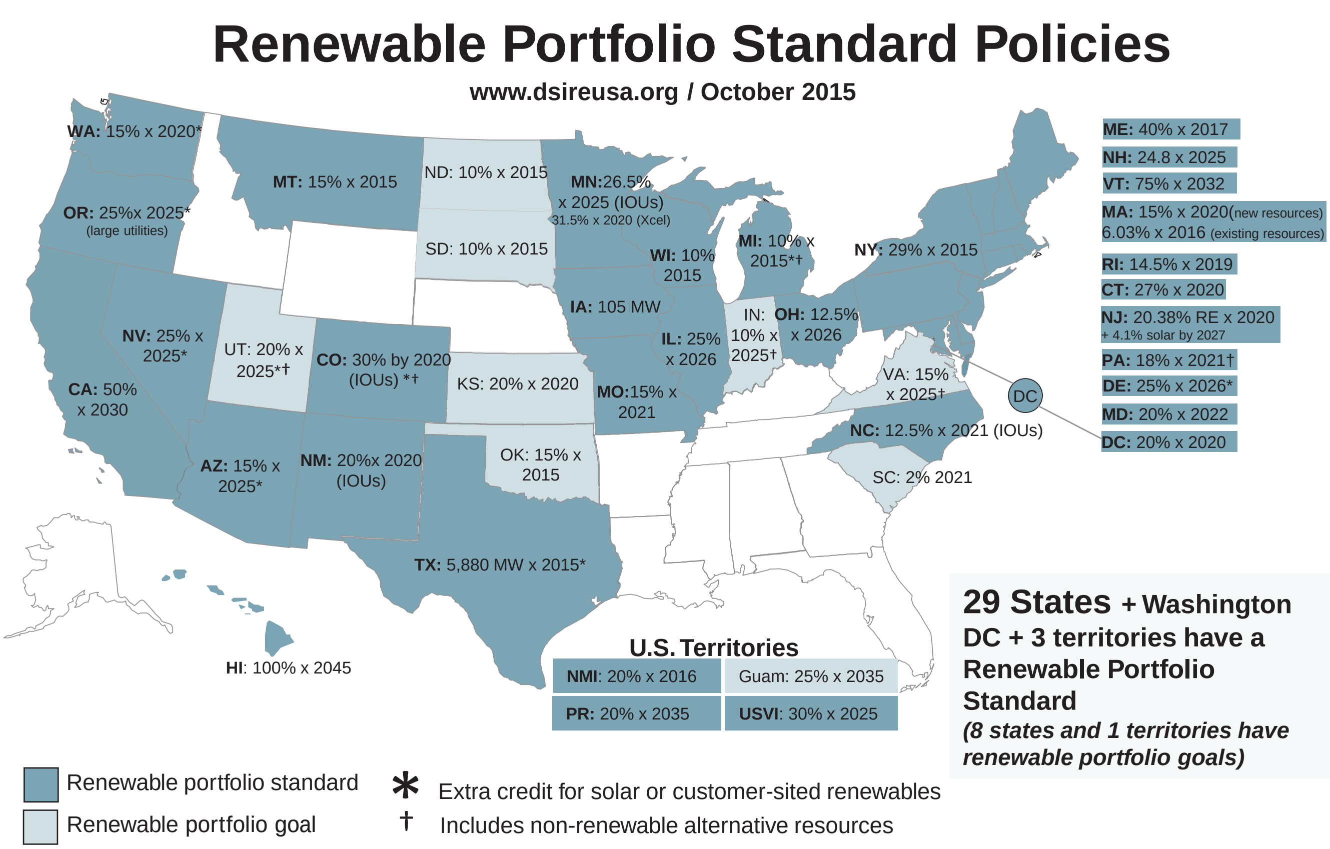

Figure 2. Renewable Portfolio Standards (RPS) require renewables, which in turn, require greater power system flexibility [8].

sustainable performance beyond regulatory requirements may accelerate the business need to become flexible.

At power plants and substations, operating constraints imposed by environmental compliance can reduce operating flexibility. Environmental controls technologies (for example, scrubbers, particulate controls, and water treatment systems) reduce emissions, but are subject to outages that expose facilities to fines, curtailed operations, or shut-downs, which further reduces flexibility. Market-based systems can help make up for some loss of flexibility by enabling a facility to offset emissions from one facility to another, or purchase emissions credits in the market. However, in some cases environmental laws (for example, the Mercury and Air Toxics Standard), impose compliance costs sufficient to close facilities for which retrofit costs cannot be justified. Many of these older facilities have provided flexibility within a utility system or on the regional grid by providing power during peak demand or periods of transmission congestion.

Environmental regulations may constrain water intake during droughts, during particular fish runs, or to protect fish, and water level and flow restrictions also may constrain hydropower operations.

Environmental regulations can impact renewable power generation as well. Wind turbines are frequently required to curtail operations to reduce collisions of birds and bats with wind turbine blades. This can require the electric system to rely on backup sources of power, reducing flexibility.

How R&D can Equip the Electricity Sector to Enhance Flexibility

- Better understand and mitigate unintended consequences.
- Make the power system inherently more flexible.
- Enhance system planning tools, including ways to measure power system flexibility.[1]

[1] *The important area of measuring the flexibility of a power system (for example, flexibility metrics) is the subject of a separate EPRI white paper [9].*

FACTORS DRIVING THE REQUIREMENT FOR POWER SYSTEM FLEXIBILITY

The Experience in Germany

Germany has deployed about 68 gigawatts (GW) of distributed solar photovoltaics (PV) and wind, and by the end of 2012, its PV capacity alone was spread across approximately 1.3 million residences, businesses, and industries, exceeding the capacity of any other single power generation technology in the country. The German experience illustrates the impacts of such a large and widespread deployment on a power system in the absence of sufficient planning and action to provide for their effective integration. Figure 3 illustrates the significant variability of hourly PV and wind generation in Germany—from producing nearly zero output to about 36 GW. The observed results, in terms of reliability, quality, and affordability of electricity, are not based on a hypothetical case or on modeling and simulations; Germany offers a real-world case study of the extensive deployment of both utility-scale and distributed variable generation.

Technical and operational repercussions include the loss of flexibility in the generation fleet, prompting the operation of coal plants on a "reliability-must-run" (RMR) basis. Germany added 6 GW to RMR status in 2012, but the large amount of RMR coal and the difficult-to-forecast PV and wind combined to produce negative price swings that adversely impacted the market operation.

In Germany, solar and wind receive dispatch priority; these resources are "must take" from a regulatory standpoint and come out ahead of the market. According to a recent Finadvice report, the zero variable cost of production of wind and solar has changed the merit order of the country's wholesale markets, reducing wholesale prices for baseload generation from €90-95/MWh in 2008 to €37/MWh in 2013 [10].

These consequences and lessons other countries can learn from this experience are the subject of a forthcoming EPRI white paper.

Given the diverse drivers and adverse consequences related to insufficient power system flexibility, utilities, Independent System Operators/Regional Transmission Organizations (ISO/RTO), and regulators face significant challenges with respect to enhancing flexibility across power generation,

> ***German Experience Sparks Urgency***
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> Germany's rapid and far-reaching deployment of variable generation, along with the unintended consequences, underlines the need to enhance power system flexibility sooner rather than later.

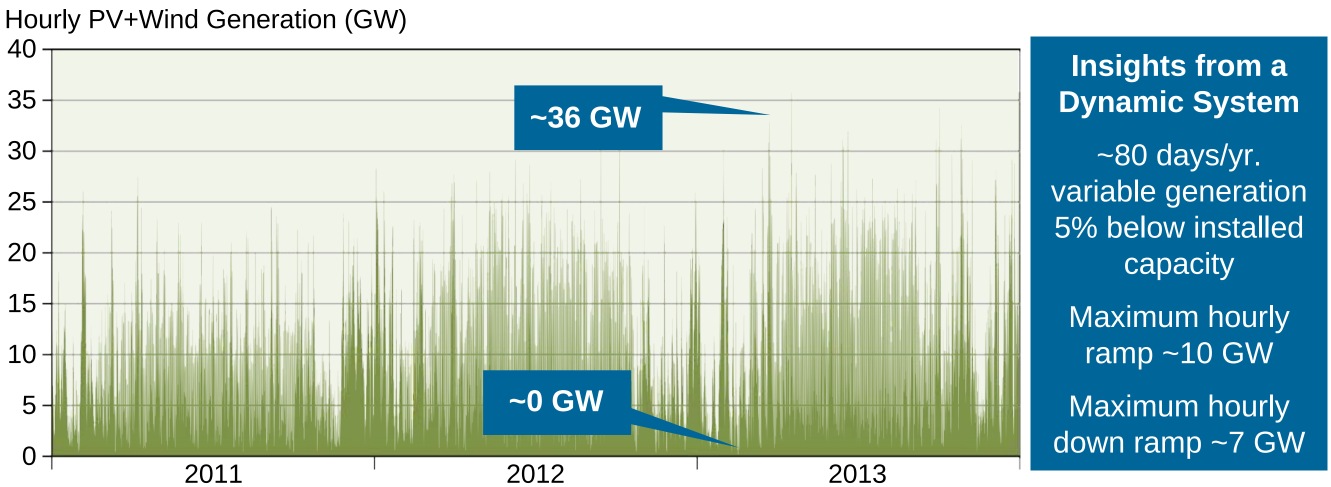


Figure 3. Hourly PV and wind generation over a three-year period in Germany shows the wide variability of the resource.
Source: Data from Klaus Kleinekorte, Amprion, German TSO.

power delivery system planning and operations, and for consumers—all while addressing environmental impacts. Figure 4 illustrates these drivers, along with selected technologies and techniques for enhancing power system flexibility that are covered in the balance of this paper.

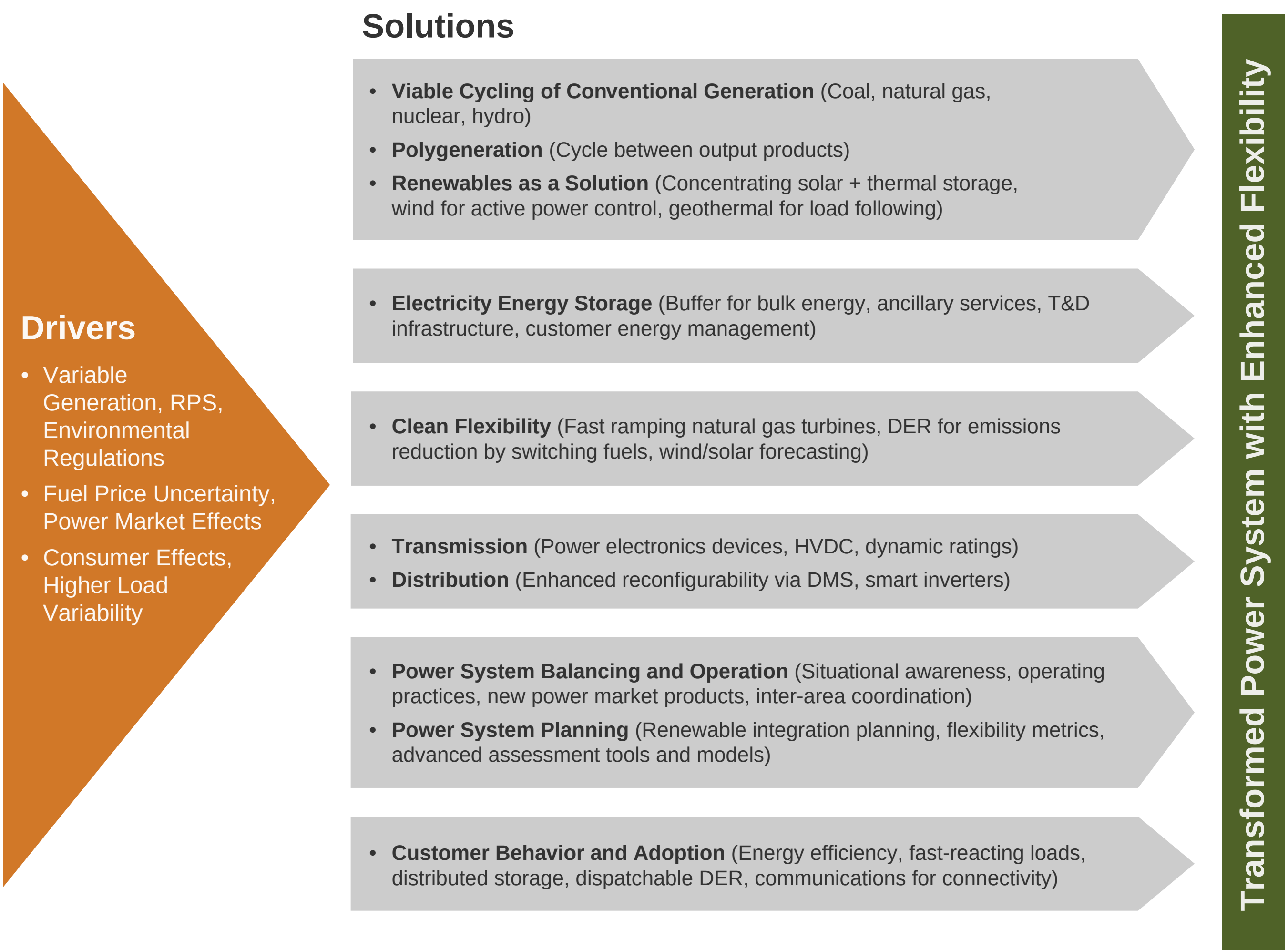


Figure 4. Drivers of needed flexibility and selected flexibility solutions described in this paper.

Coal-Fired Power Generation

Challenges

Most existing coal-fired power plants were designed for sustained operation at full load to maximize efficiency, reliability, and revenues. Depending on plant type and design, these plants can adjust output within a fixed range in response to plant or market conditions. The need for flexibility is shifting their mission profile in three ways: 1) more frequent shutdowns when market or grid conditions warrant, 2) more aggressive ramp rates (rate of output change), and 3) lower desired minimum sustainable load, which provides a wider operating range and hence, enhanced usefulness. Increasingly, fossil plants are being asked to make the transition to one or more of these duty cycles:

- **Two-shifting** in which the plant is started up and shut down once a day.
- **Double two-shifting** in which the plant is started up and shut down twice a day.
- **Weekend shutdown** in which the plant shuts down on weekends. This is often combined with load-following and two-shifting.
- **Sporadic operation** in which the plant operates for periods of less than two weeks followed by shutdown for more than several days.
- **Load-following** in which the plant operates for more than 48 hours at a time, but varies output as demand changes.
- **On-load cycling** in which, for example, the plant operates at base load during the day and then ramps down to minimum stable generation overnight.

Cycling units not designed for these operating modes can lead to more component failures, unplanned outages, increased heat rate, decreased revenue, and staff scheduling and training challenges.

Operating in these modes can cause damage and incur costs. This cycling duty can accelerate thermal fatigue, thermal expansion, fireside corrosion, and rotor bore cracking. Cycling units not designed for these operating modes can lead to more component failures, unplanned outages, increased heat rate, decreased revenue, and staff scheduling and

training challenges. At the same time, constraints on cycling operation can be imposed by new or upgraded emission controls such as selective catalytic reduction [SCR], flue gas desulfurization [FGD], and mercury controls.

Compounding these challenges, many existing flexible coal-fired power plants are being retired as a result of their age or difficulty in meeting new emissions requirements. These include small drum units with high design margins and fewer emission controls, which allow flexibility. Some grid operators have developed plans to upgrade or build new transmission to accommodate the loss of generation in certain areas or are contracting with certain generators to remain online until the impacts of the retirements are addressed.

In addition, seasonal economic shutdowns are becoming more common. Decreasing assets' service hours places even greater importance on their reliability when they are operating. This raises the need to protect these considerable capital investments when they are not in service, and the cost of this, combined with reduced service hours, may limit the unit's continued economic viability.

Fluctuating natural gas prices are causing gas/coal pendulum effects, in which coal-fired and natural gas-fired units swing back and forth in utilities' dispatch order. For example, due to low natural gas prices in April 2012, natural gas and coal produced the same amount of electricity in the U.S.—an unprecedented event. However, by November 2012, the spread between coal-fired and natural gas-fired generation had grown to ~80 million MWh for natural gas and ~130 million MWh for coal [11]. Another complicating effect here is the ability to swing coal units for the purpose of frequency control.

The overarching need is to implement new operating and maintenance strategies to maintain coal plant equipment availability, reliability, and safety; and preserve the life of critical components via improved

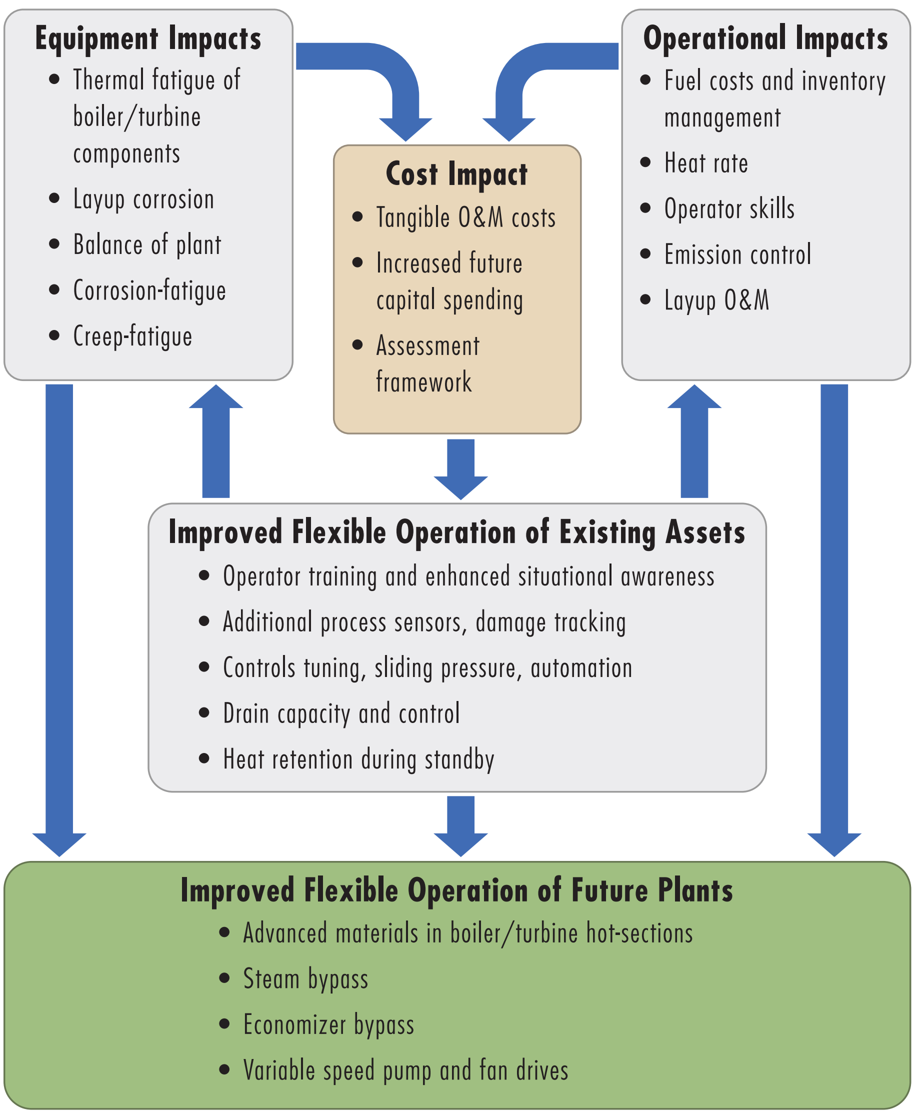


Figure 5. Key steps to improving coal fleet flexible operation [12].

materials, repairs, and chemistry. Figure 5 summarizes the interrelation of equipment, cost, and operational impacts of cycling operation on coal plants. The figure also lists ways to improve the flexible operation of existing and future coal plants [12].

As the mission profile of existing coal-fired power generation shifts to more frequent shutdowns, more aggressive ramp rates, and lower minimum sustainable load to enable flexibility, fossil generators need holistic layup techniques, better understanding of damage mechanisms due to increased cycling, defense against water side corrosion, methodologies for reducing minimum loads, advanced monitoring capabilities during transients, and methods to minimize emissions during cyclic operations. Also needed: thinner, more resilient materials; improved heat recovery steam generator inspection and repair techniques; and further automation of generation processes.

Current Research, Coal-Fired Generation

To address the issues summarized above, current EPRI research includes efforts to:

- Conduct operational case studies to identify strategies to reduce startup time and minimum sustainable loads.
- Improve holistic layup techniques for durations of hours to months.
- Better understand damage mechanisms due to increased cyclic service.
- Improve methods for protecting water-side corrosion.
- Minimize emissions during cycling operations.
- Develop boiler and heat recovery steam generator (HRSG) specifications for flexible operations.
- Develop methods for reducing unit minimum loads.
- Develop advanced monitoring during transients.
- Develop new plant designs.

Two additional EPRI projects of note are underway. One is assessing combustion-related impacts of low load and load following operation, with the goal to develop guidelines and best practices for minimizing impacts on boiler tubes [13]. The second is addressing cycling impacts on heat rate, which deteriorates significantly at lower and transient loads [14].

Cycling of coal plants impacts key post-combustion environmental control hardware, including selective catalytic reduction (SCR) systems, mercury and air toxics removal systems, and flue gas desulfurization (FGD) systems. EPRI is conducting projects in these areas:

- Extending recent lab studies to conduct field tests at a host site to examine the issues associated with cycling, load-following, and low-load impacts on catalyst activity [15].
- Analyzing impacts of plant operations, including cycling, startup, and shutdown, on mercury, filterable particulate matter, and hydrochloric acid emissions compliance strategies based on field data obtained from selected power plants. Additional plants will include electrostatic precipitator (ESP), baghouse, SCR, and wet FGD systems [16].
- Examining ways to increase operational flexibility by altering system operating practices. Two examples involve using "hot standby" mode in power generation and sharing cycling across a generation fleet over time using incremental cycling costs [17].
- Identifying the cost of cycling, as well as operational and design improvements to minimize the impact of cycling on FGD operations.

Coal-Fired Generation Research Gaps Include:

- Develop stronger ferritic materials for thick-walled components of high-temperature headers to reduce the thickness and therefore reduce temperature gradients across the wall.
- Enhance properties of creep-strength-enhanced ferritic steel to improve resistance to cycling-related damage.
- Approval of advanced nickel alloys such as Inconel 740 for use in supercritical boiler and turbine designs, allowing for reduced wall thickness and improved thermal transient response.
- Reliable high-temperature strain gauges that can be inexpensively integrated into plant information systems.
- Identify gaps in control systems that result in temperature excursions in boiler components.
- Inspection and repair techniques for HRSGs.
- Remote operation of combined-cycle gas turbine plants.
- Research addressing power plant retirement such as holistic layup techniques, decommissioning methodology, and ways to maintain power system reliability for a set number of years until retirement at minimal cost.

Natural Gas-Fired Generation

Challenges

The traditional natural gas fleet consists of simple-cycle and combined-cycle facilities. The simple-cycle unit's role in a large grid system has been to provide peaking services and in many cases black start services. Key attributes of peaking services include reliable startup, fast ramping, and reliable service for the hours requested. With low capacity factors, these units are called into service for a small number of hours.

The combined-cycle gas turbine (CCGT) unit is typically composed of multiple gas turbine/heat recovery steam generator trains and a steam turbine/generator train. These multiple trains provide inherent flexibility because of the ability to start or shut down each train. In North America such units are competitive in the marketplace and are usually the technology of choice for new fossil generation because of high efficiency, low emissions, high power density (small foot print), short construction cycles, small staffs, and high availability/reliability.

The ultimate role of natural gas-fired units in a given market has been dependent on the price of fuel, the generation mix, and renewable energy incentives. In Europe, the price of natural gas is high relative to other fuels, and the amount of must-run renewable generation is high. As a result, European gas units have very low capacity factors. The challenge for these units is to provide effective plant-wide layup processes to preserve the integrity of the equipment for use when the market changes.

In many North American regions, the combination of low natural gas prices and relatively little must-run renewables capacity results in high capacity factors for gas units. In many cases, these units provide load following or base-load services. In many markets CCGTs are displacing coal units due to low natural gas prices and the added compliance costs for coal-fired generation. While CCGT units offer the flexibility advantage of multiple trains that can be started and stopped, a single train does not provide the turndown ratio of a coal-fired generator. From a power system perspective, this flexibility is very attractive, but the starts and stops consume equipment life faster than a unit with enhanced turndown ratios.

In addition to the flexibility required to meet daily load demands, the gas fleet also must be flexible to meet changing market conditions.

Natural Gas-Fired Generation Research Gaps Include:

- Fast start technology
- Holistic layup techniques
- Remote starting
- Lower minimum load/higher turndown ratios for each CCGT train
- Integration of equipment into a unit that minimizes the impacts of thermal cycling

Nuclear Generation

Challenges

Nuclear power plants face similar complexities to coal plants when pressed into cycling duty to enhance power system flexibility. Many nuclear plants have historically operated as baseload units. As a result, most have been optimized for continuous, full-power operation, which is the most efficient and technically least challenging mode of operation. A transition to flexible operation requires changes in operating practices, increased staff training and awareness, and depending on the extent of flexible operations, physical modifications to the plant.

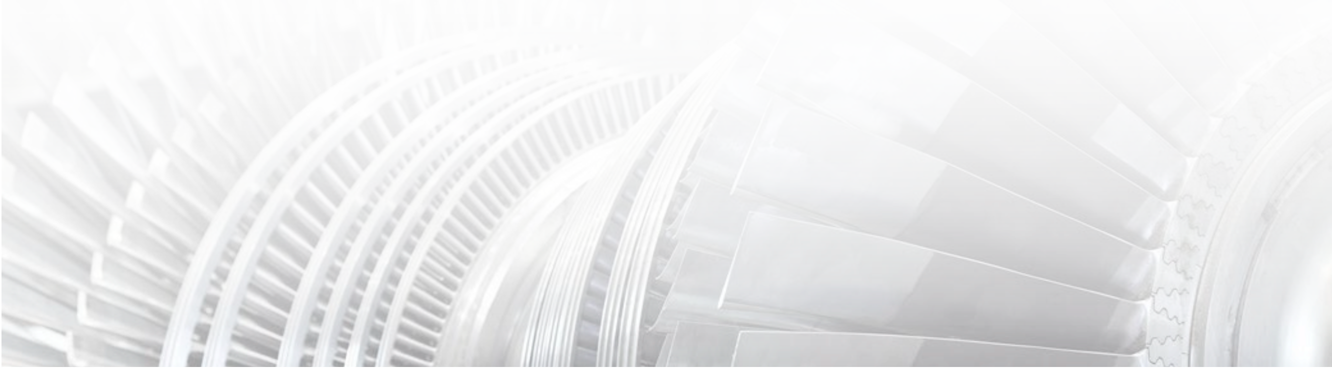
The transition to flexible operation drives the need to review the plant design basis, licensing basis, and nuclear regulations. In some cases, the plant licensing basis may need to be changed, and prior review and approval may be required from the regulatory authority.

When planning for flexible operation, the plant operator needs to establish a protocol with the independent system operator/regional transmission organization (ISO/RTO) or transmission system operator (TSO) that clearly defines the plant's safe operating envelope. The considerations are acceptable ramp rates, depth of power reductions, duration of reduced power operation, and frequency of power level changes. Defining the acceptable operating envelope is important to ensure compliance with the plant's operating license and technical specifications. How fast the plant maneuvers is an important parameter to define and control to ensure adequate margins and protect the integrity of the nuclear fuel assemblies [18].

When converting nuclear plants to flexible operation the overarching need is to implement new operating and maintenance strategies to maintain plant equipment safety, availability, and reliability; preserve the life of critical components through improved materials, repairs, and chemistry; and maintain adequate margins to protect the integrity of the nuclear fuel assemblies.

Current Research, Nuclear Generation

- Develop guidelines to support existing plants when transitioning to flexible operation (2013 Polaris project) [18].
- Support a particular PWR as a "lead pressurized water reactor (PWR) plant in the U.S." on recommended changes in operating practices and plant modifications in the areas of primary and secondary water chemistry; changes in the flow-accelerated corrosion program; and effluent storage and processing due to increased water usage during flexible operations.



- Conduct a feasibility study for enhanced monitoring and management of critical systems and components during flexible operations.
- Incorporate specifications for flexible operations into the EPRI Utility Requirements Document for new plants (both the Generation 3/3+ plants and the small modular reactors).

Nuclear Generation Research Gaps Include:

- Developing advanced sensor and monitoring methods to detect possible impacts of high-cycle fatigue caused by changes in flow-induced vibrations during more frequent plant heat and cool down cycles; and changes in flow rates, pump speeds, and valve repositions.
- Validating fuel performance codes under flexible plant operation to ensure adequate margin to protect fuel integrity.
- Validating existing margins in low-cycle cumulative fatigue usage factors during more frequent plant heat up and cool down cycles.
- Gathering operating experience data to determine impacts on human performance and possible changes in the plant's probabilistic risks assessment (PRA) model; and provide recommendations to improve human performance and reduce plant risks based on the research.
- Gathering data necessary to help utility decision makers understand the economic impacts of flexible operation on the plants.

Polygeneration

A new business model for generation brings diverse opportunities and challenges

Polygeneration (polygen) expands the power plant business model to encompass the conversion of a fuel or energy source into multiple products. Polygen extends the more common applications of finding added value in byproduct utilization or combined heat and power (CHP). Polygen plants are akin to cogeneration plants but encompass a wider set of co-products. Power plants are designed, or retrofitted, to couple electricity generation with making other

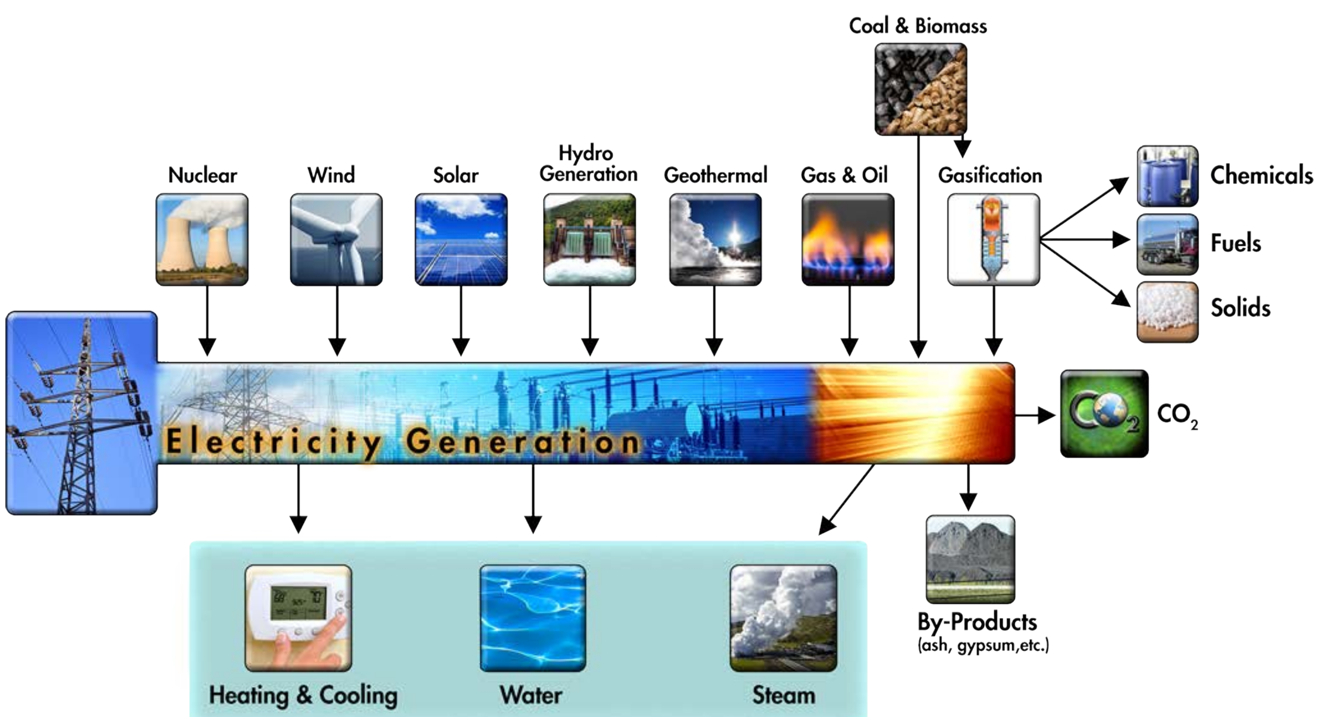


Figure 6. Polygeneration synergistically combines power generation with additional process operations to enhance flexibility [19].

products in order to optimize value from multiple revenue streams (see Figure 6). This approach applies to fossil fuel-, nuclear-, and renewables-based units [19].

Ideally, polygen applications would provide the flexibility of adjusting the balance-of-plant outputs between electricity and other products, based on price and demand. Given the accelerated pace and global scope of research on clean energy technologies, polygen may become increasingly important because of its ability to adapt dynamically to a volatile landscape of energy, products, and carbon credit markets. Polygen provides the ability to "cycle between products" while operating at steady state, minimizing wear and tear that comes from load cycling. Polygen integrated gasification combined-cycle (IGCC) and fluidized-bed plants can be designed to utilize fuel blends that include coal, pet coke, biomass, and other fuels; this fuel flexibility makes polygen adaptable to local and regional markets.

Polygen can be considered for coal plants, renewable plants, gasification plants, and in other applications. Polygen plants using coal or biomass can continue to realize value in the sale of traditional byproducts such as fly ash, bottom ash or slag, gypsum, or other sulfur products, which have established applications. "Power-to-gas" electrolysis-based technologies are being developed to convert excess energy from wind and solar to hydrogen or synthetic natural gas.

Products from synthesis gas such as hydrogen, methanol, ammonia, fertilizer, and carbon dioxide make gasification a natural fit for many polygen applications, as does its capability to accommodate diverse feedstocks, including coal, petroleum coke, oil, natural gas, biomass, and municipal solid waste.

Retrofitting plants for polygen also is possible. Emerging low-carbon technologies that facilitate capture of CO_2—such as combustion in oxygen (oxy-combustion)—coupled with the added sales opportunities of polygen may make retrofitting economical and win public and regulatory support.

Short-term, complex operations limit what is technically and financially feasible. Longer term, improvements in control systems, dynamic operation capabilities, hybrid energy systems, and improved integration engineering could yield polygen plants capable of increasing flexibility by producing a suite of products with varying outputs based on real-time market signals, with infrastructure in place to accomplish delivery over a broad area.

Information gaps today limit a broader realization of polygen opportunities, along with a lack of tools to quantify economics and risk, legacy approaches to regulation and financing, and insufficient stakeholder exchange.

Polygeneration Research Gaps Include:

- Assess market dynamics for non-electricity products.
- Screen a representative set of polygen options, followed by detailed technical and economic assessments of the most promising approaches.
- Quantify impacts of integrating flexibility requirements into operations.
- Develop a cost-benefit/risk analysis methodology for polygen configurations that includes the value of enhanced grid support and environmental advantages.
- Convene forums for stakeholder exchange and knowledge sharing.
- Hydroelectric generation.

Hydroelectric Generation

Challenges

Adapting hydroelectric generation for flexible operation poses unique challenges. The changed mission profile increases wear and tear on low-temperature, low-speed hydro components in a manner different from the thermal and mechanical fatigue for thermal plants. Hydroelectric plants' ability to support flexible generation needs may be complicated by operational constraints deriving from environmental requirements related to irrigation, recreation, minimum flow, and fish protection requirements. Hydro plants often operate in a cascade, in which the operation of one plant directly affects the facility downstream through the interactions of the head, flow, and tailrace levels of cascaded systems. This requires coordination in flexible operation. A further complication is that the availability of water for hydro operation is time dependent, requiring coordination across various time scales of system operation (for example, for energy dispatch versus regulation). Current market structures for energy production and ancillary services do not fully capture the actual costs and benefits from hydropower projects.

The overarching need when converting hydropower to flexible operation is to develop new hydro operation and maintenance strategies to maintain availability, reliability, and safety; characterize the impact of flexible operations on major components; maintain reliability of critical components through improved inspection, materials, degradation management, and repairs; and improve control optimization approaches while supporting ancillary services and flexible operation.

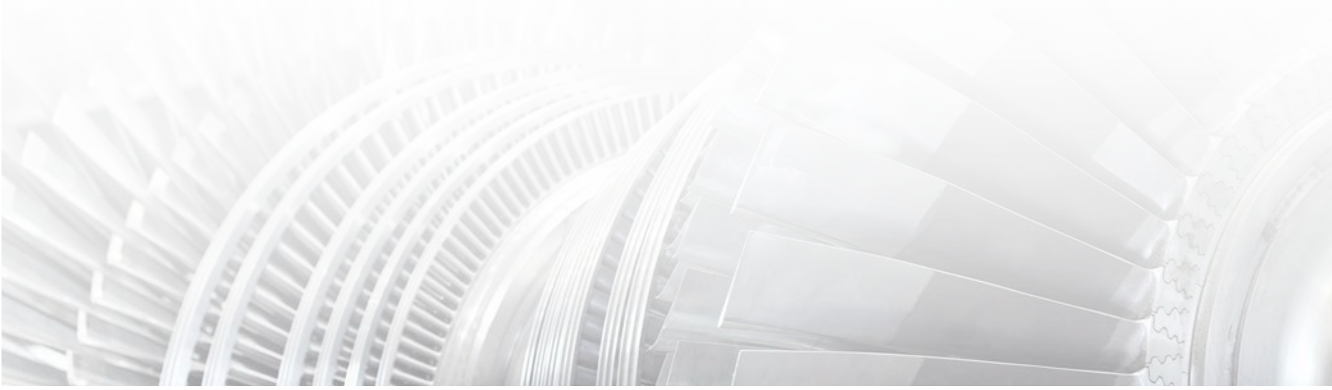
In recent developments, the U.S. Department of Energy (DOE) and industry participants completed a project to begin the process of quantifying the value of flexible operation of hydropower in the electric grid. The U.S. Congress recently passed several measures to promote hydropower and pumped storage development, and to improve the licensing process.

Current Research, Hydroelectric Generation

- Characterizing impacts of flexible operations on major hydro component reliability
- Assessing component failure and failure modes
- Characterizing anticipated changes in failures due to flexible operation
- Developing statistical methods to assess maintenance effectiveness in maintaining reliability during changing operation modes
- Developing and demonstrating improved plant-specific concrete degradation management for such structures as penstocks and spillways, including effects on structural integrity resulting in operational changes and demands resulting from increasing flexibility demands

Hydroelectric Generation Research Gaps Include:

- Develop and demonstrate maintenance strategies to improve component reliability in flexible operation.
- Develop improved turbine runner materials/coatings to improve operational performance under flexible operation.
- Develop a model for cascaded river power plants for optimizing available hydro power for flexible operation.



- Assess and optimize regional differences in hydro system operation, integration of variable renewable generation, and development of ancillary services and markets.
- Develop advanced turbine designs that reduce fish mortality (for example, fish friendly turbine), allowing for flexible generation at hydro facilities in lieu of current fish protection schemes (for example, fish ladders, bypass flows).
- Develop technology to improve downstream eel passage to reduce curtailment of hydro during migration, resulting in increased operating flexibility.
- Improve understanding of hydropower's role in supporting a reliable grid and prepare the power system for uncertain energy markets.

Renewables

While the widespread deployment of wind and solar is a key driver for power system flexibility, advancements in renewables and related technologies can make them part of the solution. EPRI, the DOE and others are working to enhance the ability of renewable energy resources to provide power system flexibility. Important examples include work in concentrating solar power with thermal energy storage, forecasting, wind power, and geothermal energy.

Concentrating Solar Power with Thermal Energy Storage

Concentrating solar power (CSP) combined with thermal energy storage (TES) is technically viable for enhancing power system flexibility. A demonstration of this technology at Enel's Archimede CSP plant in Siracusa, Italy, (see Figure 7) features about 30,000 square meters (320,000 square feet) of parabolic collectors that concentrate sunlight on pipes filled with a molten salt fluid. Thermal energy is stored in a tank and used as needed to produce steam for steam turbines in a natural gas-fired combined-cycle power plant on site. The stored thermal energy can be used at any time to increase the combined-cycle plant's generation by about 5 MW, thus providing operational flexibility [20]. EPRI is conducting an independent assessment of the Archimede plant's startup and shutdown procedures and the process of solar steam integration into the fossil steam cycle. EPRI is also investigating advanced molten salt mixtures with lower freezing temperatures and lower costs that have the potential to reduce storage and operating costs and increase reliability.

The National Renewable Energy Laboratory (NREL) recently implemented a methodology to evaluate the operational impacts and value of these combined technologies in California's 33% RPS scenario, using the PLEXOS production

Figure 7. Enel's Archimede Concentrating Solar Plant stores thermal energy for use at a natural gas-fired combined-cycle plant on site, enhancing plant flexibility.

Source: Centrale Archimede – Priolo Gargallo Siracusa" Guido Fuà – Agenzia Eikona per Enel ©

cost model [21]. When CSP with storage operates with reserves, it has high operational and capacity value, even more than a comparable baseload plant because of the ease with which it can dispatch stored energy.

Renewables Forecasting

EPRI is working on two projects related to the uncertainties of renewables forecasting. One project defines variability and clearness indices to improve ramp forecasting for solar PV systems. A second project is deploying and demonstrating existing advanced LIDAR technology for wind characterization and forecasting improvements in the Tehachapi (California) wind farm.

Wind Power

Along with EPRI and the University of Colorado, NREL recently released a study that analyzed ways that wind power can help provide active power control for balancing generation and load. While the intermittent quality of wind power often is discussed as a challenge for grid operation, the NREL study assessed how wind power can actually help with APC at fast time scales. The study focused on three types of active power control: synthetic inertial control, primary frequency control, and automatic generation control regulation [22].

Geothermal

Typically, geothermal power plants are baseload facilities, but they may be operated in a load-following mode in the same manner as conventional steam plants. Flash and binary plants each have slightly different configurations to achieve this, and the configurations influence capital cost, efficiency, and speed of response. The type of geothermal plant best suited to operate in a cycling mode is a plant at a constrained reservoir that allows changes in well flows without damage. A time-of-day pricing environment is optimal. The sensitivity of the decay rate of the productivity of the reservoir, and the optimum strategy in the pricing environment, needs to be analyzed with a comprehensive and coupled reservoir-plant-economic model. Research priorities for a geothermal plant cycling program include more quantitative examination of the effects of cycling on O&M costs; case studies of actual projects where ambient effects, reservoir conditions, and pricing environments can be modeled and optimized in more detail; and exploration of other options for energy storage or diversion during off-peak periods [23].

Renewables Research Gaps Include:

- Better understand impacts of renewable generation on system and component reliability
- Operations and maintenance strategies to maintain or improve performance, including continued

Bulk Energy Services	**Transmission Infrastructure Services**
Electric Energy Time-Shift (Arbitrage)	Transmission Upgrade Deferral
Electric Supply Capacity	Transmission Congestion Relief
Ancillary Services	**Distribution Infrastructure Services**
Regulation	Distribution Upgrade Deferral
Spinning, Non-Spinning, and Supplemental Reserves	Voltage Support
Voltage Support	**Customer Energy Management Services**
Black Start	Power Quality
Other Related Uses	Power Reliability
	Retail Electric Energy Time-Shift
	Demand Charge Management

Table 1. Seventeen grid services that storage can provide [25].

PV component reliability research through Solar Technology Acceleration Center, and wind turbine O&M guidelines, and solar thermal heat transfer fluids through the Archimede Concentrating Solar Power Project in Italy

- Various aspects of biomass and geothermal resources, as well as the cost, performance, and reliability of renewable generation

Electric Energy Storage

Electric energy storage has the potential to enhance grid flexibility in several ways. Energy storage provides an inventory of electricity to the power system, adding a buffer to the current "just in time" system. It can be used to manage peak load, follow power system ramps, provide responsive reserves, relieve T&D congestion, and mitigate service outages. Storage can make the overall grid more flexible by accommodating more variable, renewable generation resources. It can reduce strain on the grid caused by power fluctuations and can help optimize dispatch of both variable and conventional generators. Grid energy storage can respond quickly to second-to-minute changes in electricity demand and to supply changes resulting from variable generation. As a temporary "shock absorber" it can dampen transient electric conditions on local generation, transmission, and distribution network equipment [24]. The DOE/EPRI Electricity Storage Handbook lists 17 services that storage can provide to the grid (see Table 1) [25].

Challenges

Advanced energy storage technology has garnered tremendous interest in recent years, including a procurement target of 1.3 GW in California by 2020, and similar policy and regulatory drivers in New York, Puerto Rico, Hawaii, Ontario, and jurisdictions around the world. However, storage faces significant technical, economic, and regulatory challenges. Many of these can be mitigated through coordinated and collaborative efforts among utilities, industry, government, research entities, and other stakeholders.

While pumped hydro energy storage is mature and widely used, opportunities to site additional projects are limited. Emerging battery and other advanced energy storage technologies have certain components with a track record, but commercial turnkey electricity storage solutions remain nascent. To date, the cost to build energy storage projects (without significant incentives) usually significantly exceeds the quantifiable benefits. Additionally, such assets have not demonstrated the multi-decade lifespans typically expected of utility assets. For utilities and regulators to support broad commercial deployment of energy storage, systems must operate safely, reliably, and cost-effectively. Today most energy storage systems are unproven in performance, reliability, and cost-effectiveness in demanding utility applications. Concerted effort and support are required to overcome these hurdles.

Widespread use of storage requires development and industry acceptance of improved grid integration tools that can identify where and how storage can be sited, deployed, and used to achieve maximum value. Coordinated efforts among technology developers and utilities is needed to ensure storage systems can adequately address utility functional requirements and use cases. This

includes development of standards for operating in remote and often harsh utility environments. Utility planners can provide particular insights in identifying the use cases and requirements for energy storage.

Energy storage remains expensive relative to alternatives. Although some instances may demonstrate a viable business case, a considerable gap typically remains between the delivered value of storage and the costs of installed systems. This gap is particularly important under the current (and expected to continue) trend of low to flat load growth, in which regulators and customers scrutinize utility investments with respect to keeping electric rates as low as possible. To promote wide adoption, energy storage systems must be demonstrably more cost-effective than existing technologies and operational measures.

Given its flexibility in siting and operation, the value of storage may be enhanced through providing multiple services. While attractive, this approach is more challenging. Providing multiple services requires significant care to avoid conflicting operational objectives and to manage associated system availability. Different benefit streams may accrue to different owners, complicating business models and monetization under existing regulatory frameworks.

To date, no "magic bullet" energy storage technology or product has been discovered to meet all of the power system's needs; therefore, a portfolio of options is being developed. The mere existence of energy storage technologies is insufficient, and energy storage products must be "grid ready" before commercial deployment. They must demonstrate their ability to meet critical safety, operational performance, and reliability requirements, while seamlessly integrating into utility system operations [24]. Additionally, advancements to utility communications and control infrastructure may also be required to realize the full potential of energy storage to improve flexibility, resiliency, and cost-effectiveness of electric power.

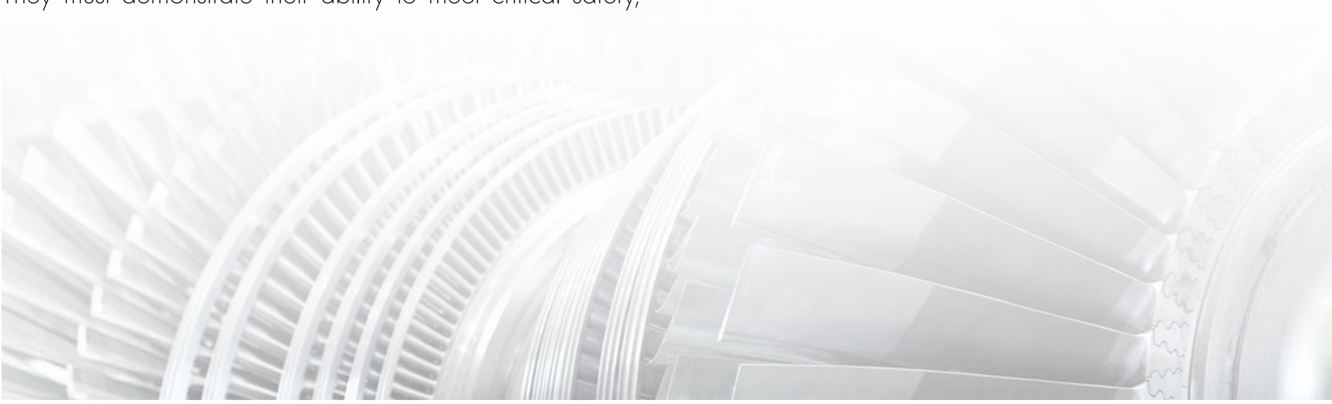
Current Research, Energy Storage

EPRI's Energy Storage Program has formed the Energy Storage Integration Council (ESIC) to address challenges being encountered by energy storage demonstrations, including:

- Problems stemming from poor system integration
- Grid integration difficulties
- Insufficient factory testing and qualification
- Safety and reliability
- Inadequate test protocols

In this forum, electric utilities guide a discussion with energy storage vendors, government organizations, and other stakeholders to develop reliable, safe, and cost-effective energy storage options. ESIC facilitates and drives discussion on key issues, identifies, prioritizes, and supports the development of utility requirements. Forum topics include applications, performance, systems development, grid integration, and analysis [24]. More information about ESIC can be found at www.epri.com/esic.

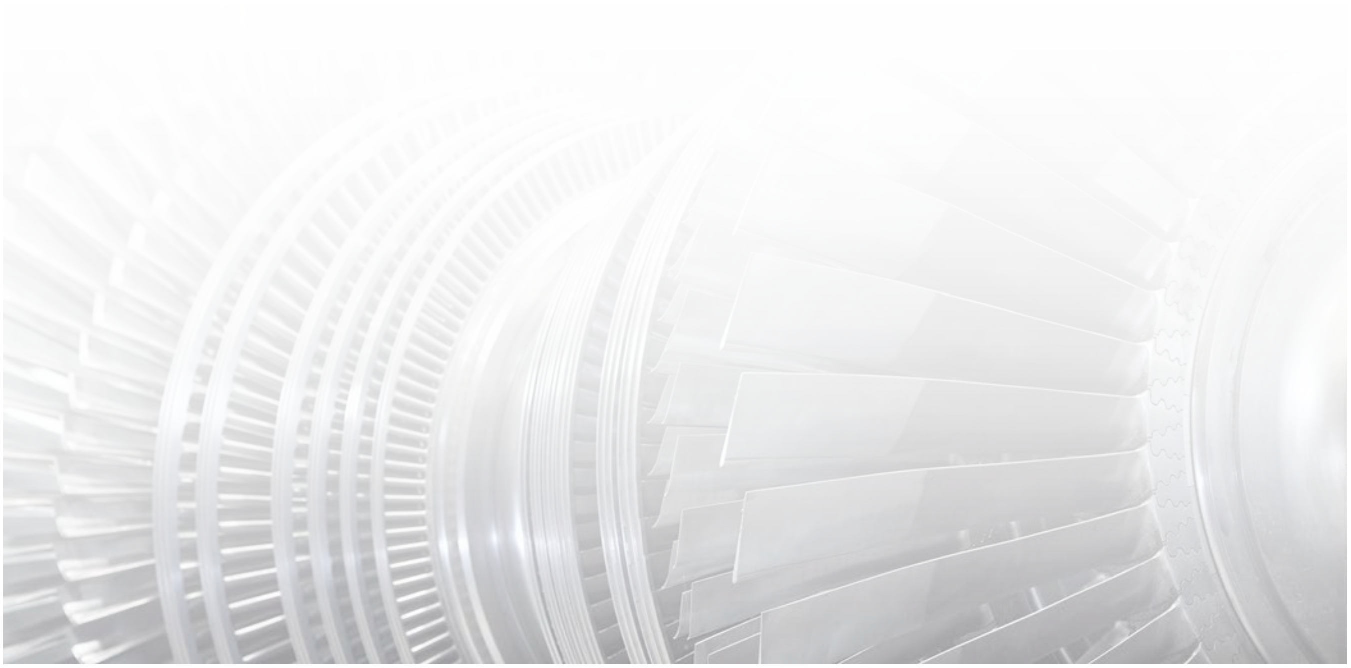
EPRI has developed The Energy Storage Valuation Tool (ESVT), a methodology and software model that equips users to quantify the value of grid energy storage, assess projects' lifetime economics, and analyze different uses,



technologies, locations, and market scenarios, factoring services provided, time-varying load and prices, the owner's perspective, and the technology. An EPRI report describes its application to inform stakeholders of the California Public Utility Commission (CPUC) regulatory proceeding investigating the cost-effectiveness of energy storage in approximately 30 different cases. Scenarios covered three general use cases, including transmission-connected bulk energy storage, short-duration energy storage to provide ancillary services, and distribution-connected energy storage located at a utility substation [26]. Additional case studies are underway to tailor the tool to needs of specific electric utilities.

Energy Storage Research Gaps Include:

- With the near-term deployment of energy storage systems arising in response to procurement targets and mandates, utilities require new tools for planning, procuring and integrating energy storage.
- Incorporate energy storage characteristics into utility and operational planning models that consider emerging needs for power system flexibility.
- Technical requirements for the procurement of energy storage equipment for its intended use and point of connection, and for communication with vendors.
- Methodologies and tools for consistent comparison of cost-effectiveness to support decisions and proposal assessment.
- Defining common test protocols based on utility needs to provide performance measurements that support consistent assessment.
- For utility operators, develop communications and control schemes to enable energy storage as a flexible, controllable asset.



ENHANCING FLEXIBILITY: ENVIRONMENTAL IMPACTS

The need to operate the power grid in a flexible manner can increase generation cycling, which can impact air, water, and solid waste emissions.

As non- or lower-emitting sources displace higher-emitting generation, overall emissions could be substantially reduced. However, attention also should be given to transient increases in fossil-fueled plants' emissions rates during startup, shutdown, and other ramping periods, as well as during low load, relative to steady-state operations at full load. Temporary increases in emissions rates can be due in part to incomplete combustion and incomplete warm-up of emissions control devices. Systems such as biological treatment for FGD wastewater may not be able to sustain performance during cycling operation or shutdowns. Placing large fossil fuel plants on hot standby for lengths of time may increase costs and/or emissions by keeping cooling water circulators, fans, and other devices running despite the lack of power generation. Also, given technical challenges in accurately measuring emissions of chemicals during startup and shutdown, uncertainty may exist in these emissions estimates.

Various outcomes are possible with respect to emissions and their subsequent environmental impacts, depending on the type of cycling (for example, load following, minimum load operation, hot standby, or complete shutdown), type of generation facility, and fleet composition in the grid region. To avoid unintended consequences, careful attention should be paid to the net environmental discharges due to rapid operational changes.

Newer technologies, such as fast ramping natural gas turbines, are being designed in part to substantially reduce ramping time, which can reduce wear and tear on equipment and reduce short-term rises in emissions that can otherwise occur [27, 28].

Distributed generation units differ widely in their emissions as a result of unit type, size, and typical operational cycles. For example, diesel-fueled reciprocating internal combustion engines can have emissions factors higher than central site facilities, whereas fuel cells can have near-zero emissions depending on reformer operations [29, 30]. Use of distributed generation systems can yield environmental benefits. The use of natural gas fuel rather than coal

would result in substantial reductions in the emissions rates for carbon dioxide (CO_2), nitrogen oxides (NO_X), and sulfur dioxide (SO_2). New fast-ramping units increase combustion efficiency and minimize operational periods that can produce higher emissions rates. Additionally, many distributed generation units will undergo facility permitting processes that require extensive air quality analyses.

However, the potential for environmental impacts does exist, depending on the fuel, the extent and type of operation, location, and plume dispersion. For example, if diesel fuel is used, the emission factors would be higher than for natural gas. If emergency backup generators are operated frequently, especially if multiple units are aggregated, total emissions could be substantial.

Even if total emissions from distributed generation systems are lower relative to central generation facilities, the net result could potentially be higher exposures for some. Distributed generation systems sited closer to human population centers could increase exposure to pollutants. These units release emissions at much lower altitudes than central site generation due to shorter stacks and at lower temperatures, which reduces plume rise and dispersion, increasing human contact.

Current Research, Environmental Impacts

Factors related to new generation technologies and configurations could be addressed through three-dimensional atmospheric chemical-transport modeling while incorporating representative emissions factors. EPRI is beginning regional and local air quality modeling that will continue for several years.

With respect to distributed generation, initial long-term assessments have been performed, including prior EPRI research [31]. Results suggest both air quality and greenhouse gas benefits and impacts over 20 to 30 years. In the limited scenarios tested, regional impacts were typically small relative to benefits, and impacts were concentrated near the source.

Environmental Impacts, Research Gaps Include:

Additional regional and urban studies, based on current knowledge of equipment emissions performance data, are needed to update initial assessments, to understand fuller range of possibilities, and to ensure that technologies are deployed environmentally responsibly. With respect to the deployment of energy storage technology, small emissions from these units are possible depending on how the storage is charged, unit efficiencies, losses, other sources of generation that would contribute or be displaced, and the timing (for example, daily cycling) of these activities. If cycles can be operated to reduce use of fossil fuels in favor of low- or non-emitting sources, such as renewables, net emissions reductions would be expected.

Environmental impacts associated with the manufacture, installation, use, maintenance, and decommissioning of distributed energy resources (DER) technologies is not typically considered during these studies, but should be assessed in some way.

Determining environmental impacts associated with the transition to a more flexible power system is challenging due to the diverse scenarios of generation, delivery,

storage, demand management, and energy efficiency measures. Among their first collaborative actions, EPRI and the industry should develop a reasonable and credible range of scenarios of power system design and operation. Based on these, initial assessments of potential environmental impacts can be made, including those affecting land and water use, emissions, multimedia pollutant fate and transport, and equipment end-of-life issues (such as re-use, recycling, and waste disposal).

Transmission and Substations

Transmission plays a critical role in facilitating flexibility derived from resources with changing demand and renewables production. Ensuring system flexibility presents a new challenge to transmission system planning and operation. Demand and renewables typically are concentrated geographically, either co-located or separated by significant distances. Similarly, the distribution of conventional generation around a network may vary significantly. As demand and renewable production change at a faster rate, the location of the responding resources, and the ability of the network to manage fluctuating power flows will be a critical part of system balancing (see the section, *Balancing Resources and Power System Operation*).

As more variable generation connects to a network, the direction of power flows changes relative to that for which a network was originally designed. Transmission networks may experience a reversal of flows from certain distribution feeders where rooftop PV systems have been installed (see Figure 8). To accommodate these new power sources, networks need to be sufficiently flexible to adapt in a reliable and cost-effective manner.

Current Research, Transmission and Substations

Transmission system design and operation is evolving to consider more uncertain and variable power flows. The adoption of power electronics devices (also known as flexible AC transmission system [FACTS] technologies), such as unified power controllers, and high voltage DC lines has enhanced operators' abilities to control active power network flows and aide balancing operations. EPRI has been involved in understanding FACTS devices and their contributions to power system flexibility [32]. The validated capabilities and the experience gathered from deployment of flexible transmission technologies provide valuable insights for strategic decision making [32]. Similarly, EPRI leads industry insight into the role that HVDC may play in future power systems [33].

As net load variability increases, system planners and operators are turning to these newer technologies to provide the required support and functionality. As a result, continued development of transmission networks to manage variable power flows becomes fundamental to the future of reliable and efficient power systems (see the separate sections on power planning and operation later in this paper).

As system components more frequently operate at their technical limits, it becomes important to understand the impact on operational characteristics and maintenance requirements. In partnership with member utilities, EPRI is investigating methods and technologies to incorporate dynamic ratings of line thermal capacity into operation [34, 35]. EPRI's overhead line research program is addressing effects of sustained operation at component limits by developing new methods and tools to improve line rating reliably and at least cost fashion [34]. Improved line ratings ensure that operators can deploy generation to maintain flexibility without exceeding the network's limits.

Transmission and Substations Research Gaps Include:

Understand the implications of flexibility for the integrated development and maintenance of transmission networks. The increased utilization of assets in a manner for which they were not originally designed may have implications for the scheduling of maintenance, development of operational techniques to maximize line and cable performance, and deployment of FACTS devices. Further research will be required to understand the implication of flexibility for the integrated development and maintenance of transmission networks.

Distribution

The increased penetration of distributed generation (DG) across the distribution system is profoundly affecting electric distribution designs and operating practices that have existed for a century or more. Distribution system operators (DSOs) need to be able to reconfigure the system (i.e., serve sections of the system from alternative local substations or feeders) due to load growth changes over time, system maintenance, and system contingencies such as unplanned outages). Increased levels of DG can limit this re-configurability (i.e., flexibility). For example, if a portion of the grid needs to be served from a different feeder/substation during an outage, voltage and/or protection issues that result from DG supply across various portions of the grid may prevent needed line section switching. Increased levels of DG also can mask true load levels. For example, prior to an event, DG output can offset load. When an event occurs, DG may become unavailable for up to five minutes. However, the DSO reconfigures the system based on the load prior to the event. Once reconfiguration

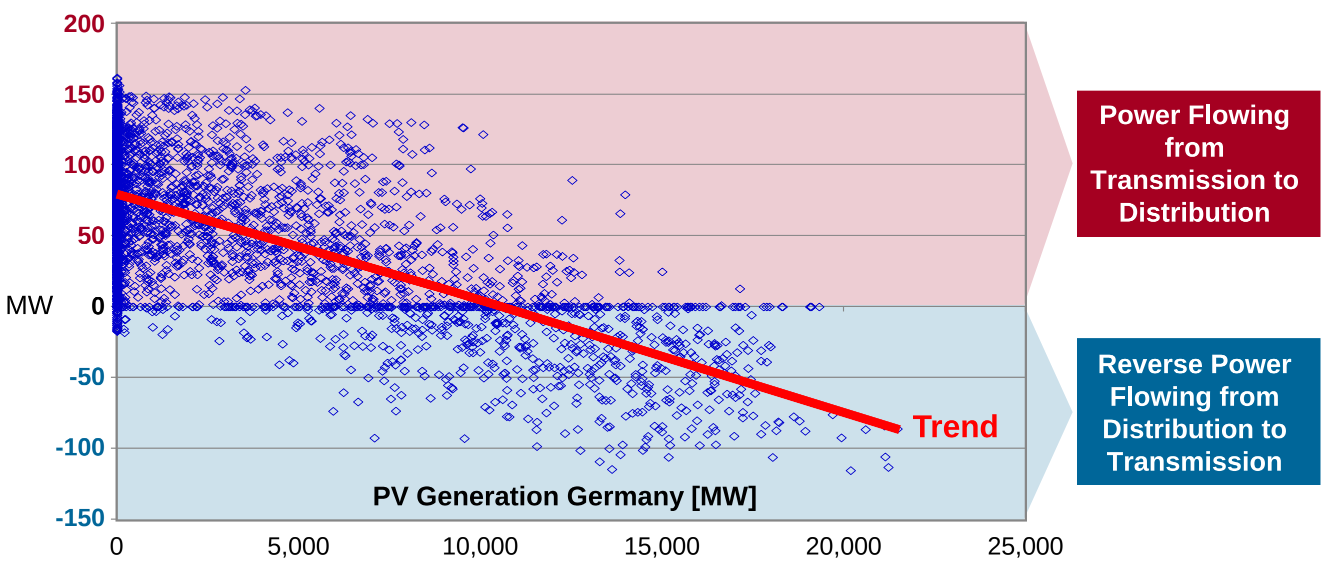


Figure 8. Increased deployment of variable generation can cause a reversal of flows, which can cause transmission congestion, localized voltage issues, and protection issues.

Source: Data from Klaus Kleinekorte, Amprion, German TSO.

occurs, the load is actually higher than expected because the DG has not come back online.

Such complexities require enhanced abilities to monitor and control DG on feeders to enable reconfiguration. Smart inverters and distribution management systems (DMS) can help address these complexities.

Smart Inverters

Utility grids with variable distributed generation, such as solar PV systems, on their medium- and low-voltage circuits must take special precautions to maintain power quality, reliability, and safety. Variable distributed resources make it more difficult to keep voltage within acceptable limits, and they introduce the potential for unintentional islanding that could create a safety hazard or damage critical grid equipment. The inverters and converters that connect solar PV, energy storage systems, and other distributed resources to the power grid have the potential to mitigate these and other negative impacts, and to bring grid operators benefits beyond renewables integration.

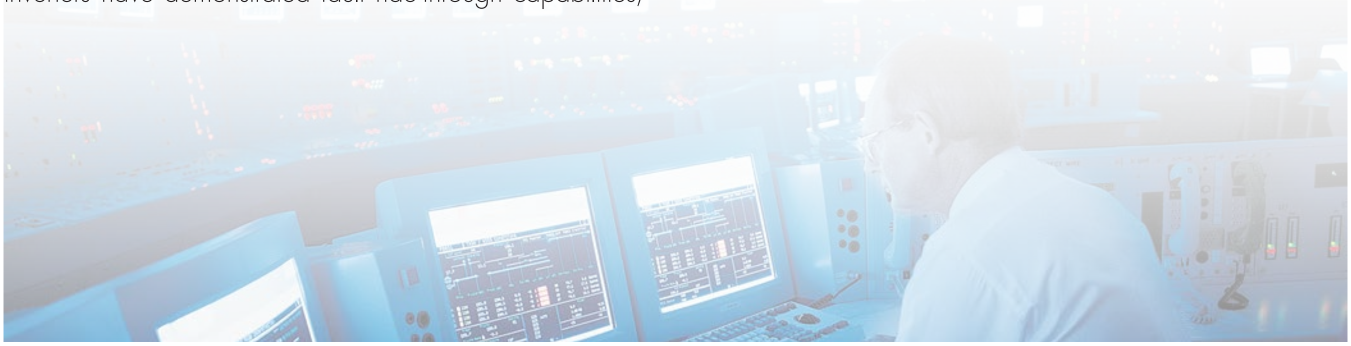
Utilities are now conducting field trials and experiments to determine how best to incorporate these smart inverter capabilities into their systems. Case studies provide evidence that smart inverters are technically capable of providing advanced grid support functions, including mitigating, at least in part, the impacts of variable PV system generation on the grid, which typically involves some form of voltage regulation by the inverters. Grid operators have demonstrated microgrids with high penetration of PV enabled by a combination of smart PV inverters and smart converters tied to energy storage systems. Smart PV inverters have demonstrated fault ride-through capabilities, while energy storage systems with smart converters (which convert DC to AC as well as AC to DC) have demonstrated frequency regulation and fault ride-through, as well as step load, spinning reserve, firming, and peak shaving capabilities [37].

For More Information: The Integrated Grid

To realize fully the value of distributed resources and to serve all consumers at established standards of quality and reliability, the need has arisen to integrate DER in the planning and operation of the electricity grid and to expand its scope to include DER operation—what EPRI is calling *The Integrated Grid*. For more information, see EPRI's white paper on the Integrated Grid, 3002002733, February 2014 [36].

Distribution Management Systems

A distribution management system (DMS) assists control room and field operating personnel with the monitoring and control of the electric distribution system in an optimal manner while improving safety and asset protection. Four years ago, fewer than five major DMS projects were underway in North America. Now, dozens of DMS projects are planned or being implemented by utilities small and large. However, DMS technology is still in its infancy, and many utilities are using small-scale field trials for proof of concept of advanced application software for distribution system optimization.



The power electronic circuit capabilities of smart inverters, if properly exposed and integrated with a DMS, can transform high penetration DG from problematic uncertainties to flexible, beneficial tools for distribution management. To achieve these potential benefits, DMS must account for the presence of DG in its models and advanced applications. Furthermore, the DMS should take advantage of advanced DG control capabilities and opportunities for improving the reliability, efficiency, performance, and overall quality of service for customers.

Meanwhile, the current generation of DMS is not considering support for DG integration. In most cases, DG support within the DMS is limited to monitoring the output of utility scale generation (>1 MW). In addition, existing industry standards define advanced functions for DG only at the individual device level, and lack the more aggregated, feeder-level representations that are needed for enterprise integration.

Current Research, Distribution

EPRI and utilities are conducting field trials to determine how best to incorporate smart inverter capabilities into their systems.

EPRI is exploring diverse ways in which the DMS can use distributed resources more effectively. In the future, the DMS is expected to interact with a Distributed Energy Resources Management System (DERMS) to use the DG in the most effective manner [38].

Distribution Research Gaps Include:

Significant development and demonstration is needed to bring DMS from an early stage of development, but the potential exists for smart inverters, if properly integrated with a DMS, to transform high penetration DG from problematic uncertainties to flexible, beneficial tools for distribution management.

Balancing Resources

"Balancing resources" are those that can respond to an operator's instruction or that automatically prevent a power imbalance or restore energy balance in a range of events. Balancing resources may respond to different triggers in various time scales, providing a service critical to maintaining a reliable and efficient power system.

Variability and uncertainty can cause this response to be called upon: demand variability that is not met by production variability gives rise to unstable operating conditions. Unforeseen events such as generation or transmission outages or wind or solar generation forecast errors also require a response from balancing resources.

These key characteristics determine a resource's flexibility and contribution to system balancing:

- **Operating range** (i.e., resource capacity to minimum generation level) governs the capability of resources to remain online during periods of low demand or high variable generation production.

- **Ramp rates** govern how fast a resource can respond when online.
- **Startup times** govern how quickly a resource can provide upward flexibility when offline.
- **Minimum times** online and offline are important in restoring the capacity available to a system operator following a commitment or decommitment decision.
- **Energy limits** on the production from reservoir or storage resources limit how long a flexible response can be sustained.

In recent years, balancing resources in systems experiencing elevated variability and uncertainty of net load have been required to start up, shut down, and ramp more frequently. Certain older fossil plants that are nearing the end of their useful life or that will soon be retired for regulatory reasons have provided enhanced balancing response through increased ramp rates and reduced minimum generation levels. In some parts of the world, newer resources such as combined-cycle or single-cycle gas turbines are replacing coal and nuclear generation with more flexible response. New technologies such as storage devices and demand side management programs have the potential to increase the flexibility available to balance the system. Active power controls have been introduced into wind and solar plant designs to ensure that these resources also can provide a flexible response [22].

Near term, development will continue primarily on increasing the efficiency of generation technologies, as well as improving flexible characteristics of both conventional and renewable plant designs. The principal change in the availability of U.S. balancing resources will be linked to the substitution of gas-fired generation for retiring coal and nuclear generation.

Current Research, Balancing Resources

With more experience in operating plants under variable net load profiles, operational procedures within plants may improve to the point that faster startups or reduced minimum generation times will enhance a plant's flexibility. In this area, EPRI is leading the DOE's Fleet Transition project. Further development to improve the business case for storage and demand side resources will take place, resulting in more extensive deployment. EPRI is leading research into both of these areas through a demand response demonstration project with a wide range of stakeholders and the energy storage research program.

In the future, balancing resources will focus on the development of technologies and plant designs to maximize the five flexible properties listed above. One example is EPRI's involvement in the design of future modular nuclear reactors.

With the transition to renewables, system and market operators are re-examining mechanisms for balancing generation with system demand. This gives rise to new scheduling practices that update commitment and dispatch positions more frequently, use new forecast information to mitigate effects of uncertainty associated with renewables, and adapt existing operating reserve requirements to manage the need for flexibility. Operators need operational decision making to include more probabilistic methods to ensure that the flexibility required is available and provided at least cost. Tools are in development to include transmission

switching decisions as a way to reduce production costs and facilitate a power system's flexible operation. To evaluate probabilistic forecasts, EPRI is developing methods to determine reserve requirements based on the prevailing risk and metrics. Utilities and system operators will need training and support to implement these advanced methods.

Power System Operation

Challenges

Prudent operation helps ensure reliable and least cost energy supply to the consumer. The daily and real-time balancing of a power system depends on the presentation of accurate, useful information to operators in such a way that resources can be effectively managed to meet the system's flexibility requirements. Knowledge and understanding of how demand and variable generation may behave over the coming hours is important in decisions regarding generation dispatch and transmission asset switching. As a result, system operators are monitoring closely the ability of the available resources to ramp if required.

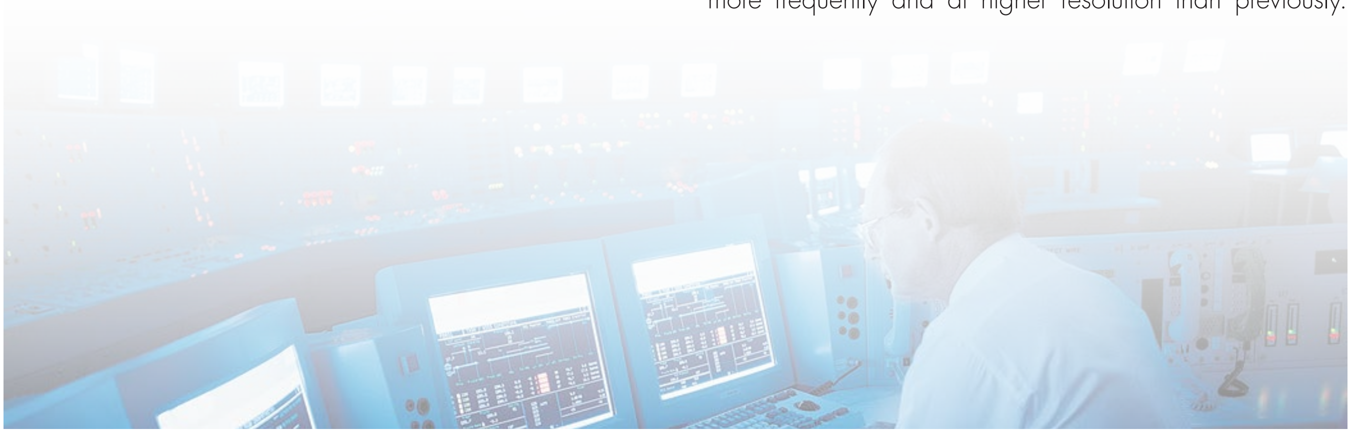
Situational awareness through demand and variable generation forecasts is useful for operators making real-time decisions, and for the design of ancillary services. As ramping requirements and system contingencies change, matching appropriate services to those needs is an important part of the emerging operational reality. In the past 10 years variable generation forecasts have improved in precision and accuracy, becoming widely adopted and used for various purposes, including scheduled outage management and natural gas trading.

The additional generation variability and greater availability of information also calls for higher resolution dispatch instructions to be issued. In many systems, commitment decisions are being made more often when new information arrives, and dispatch instructions are based on five-minute intervals to manage both variability and movement of generators around their set-points.

Recent Developments

The most visible development with respect to flexibility needs can be seen in the California ISO area and other power systems with high penetration of renewables. In these systems, new ancillary service products are addressing an operational need for flexibility. These ancillary services take the form of operational rules, new reserve types, or longer-term incentives for generators. Experience in California is leading to an operational, reserve type product that increases the flexibility available in real time [39]. The Midcontinent ISO is changing market rules to make sufficient ramping available, but without defining a new ancillary product [40]. Developments in Ireland will result in a longer-term product that rewards available flexible capacity in one-, three-, and eight-hour increments [41]. The quantity of existing reserve types has also been examined in many areas with high variable renewables. New algorithms and methods have been developed that include the variability of variable generation when determining reserve procurement quantities [42].

Another option is to increase coordination between neighboring areas, as well as to commit and schedule units more frequently and at higher resolution than previously.



Plans for the European Single Electricity Market, which is currently in development, will tightly coordinate the existing electricity markets in Europe from day-ahead decisions to real-time [43]. Similarly, the agreement between PacifiCorp and the California ISO to engage in closer coordination on imbalances will increase the response to system flexibility requirements in both areas [44].

Current Research, Power System Operation

Wind and solar forecasting have progressed in recent years to become crucial to scheduling and operation. Near term, the probabilistic information that underpins these forecasts will be brought to the fore and exploited in new algorithms and tools. Additional information from probabilistic forecasts can be used to increase operators' situational awareness of possible ramping or flexibility issues, an example of which is the Extra Large Ramp Alert System in Texas [45]. EPRI is leading the development and transfer of these methods into widespread practice. Examples include the innovative solar forecasting demonstration project with CPS Energy in San Antonio, Texas, and through reserve determination studies in Great Britain and California that use probabilistic information [46].

Control room energy management systems will be designed to incorporate the data streams and analytical tools necessary to operate a system with high penetration of renewables. A significant part of the active power management part of those tools will include forecasting and reserve determination functions currently being developed.

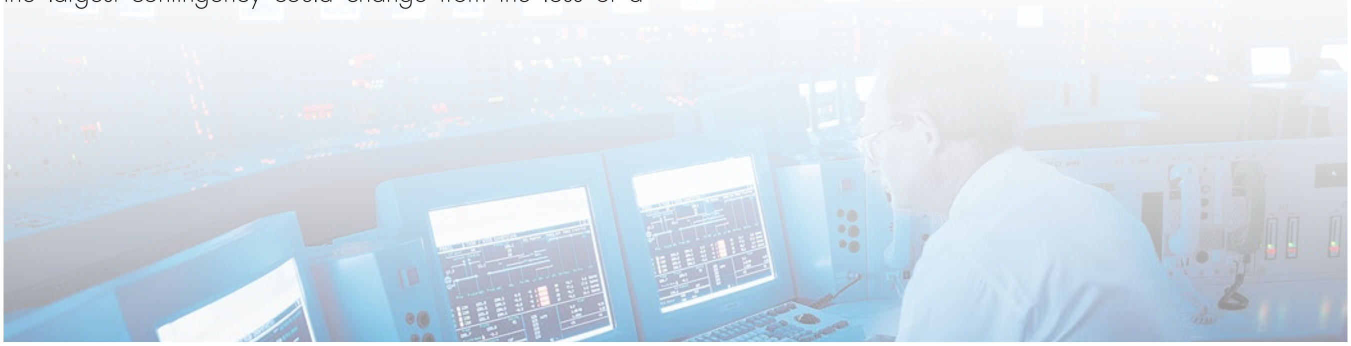
As the penetration of variable generation increases to more than 50% of energy requirements, it is conceivable that the largest contingency could change from the loss of a conventional generation resource to the coincident outage of many variable generation resources. This will lead to new requirements for contingency reserves.

Power System Planning

Power system flexibility is potentially critical for both planning and operation in systems where variability and uncertainty deviate from risks associated with traditional diurnal demand cycles and conventional generation outages. Power system planning is changing significantly as variability increases in demand and production. This has been experienced in systems in the United States, China, Germany, Spain, Portugal, Denmark, Ireland, and Great Britain.

While the balancing function of any utility or ISO resides in operational departments, considering operational balancing and flexibility requirements in planning functions is a positive development in increasing reliability in operations. Traditional planning ensured that a future system would meet targeted reliability standards based on meeting peak demand. An implicit assumption was that if the peak demand could be met, the system was operable in all other periods. Increased variability and uncertainty challenges this assumption.

Long-term planning in many areas now includes studies to determine a region's flexibility requirements under a range of scenarios, and to determine if the system is operable in a given period. Studies in U.S. Western and Eastern Interconnections, Canadian provinces, and Europe have indicated that future power system operation may require new methods to plan systems and new operational procedures.



The next generation of planning tools and processes will consider variability and uncertainty as fundamental to the power system's reliable, efficient, and sustainable operation. Fuller integration of information on demand-side resources, conventional and renewable generation will enable better power system coordination. More distributed generation will require stronger collaboration among transmission owners and operators and distribution network owners and operators. Network management will become increasingly important to manage a system's flexibility needs.

Current Research, Power System Planning

Considerable effort has been invested in determining the impact of flexibility requirements on long-term planning and short-term operations. For the U.S. Western and Eastern Interconnection, the National Renewable Energy Laboratory (NREL) conducted wind and solar integration studies to quantify the need for flexibility, the ability of a future system to meet that need, and the implications for plant operation, and on transmission requirements. EPRI is engaged with these studies as they progress. These planning processes are evolving in response to the increased uncertainty associated with renewable generation and the surge in demand response resources. Production cost and simulation tools have been refined to incorporate a rich representation of operational constraints in the planning time frame [47].

EPRI has developed flexibility assessment metrics and methods, enabling system planners to evaluate the flexibility of planned portfolios in different scenarios [48]. EPRI has also been engaged with understanding the impacts of plant cycling from a system perspective, helping planners, operators, and owners understand the type of plant future operational regimes [49].

Progress is being made to improve tools and metrics for flexibility assessment in planning studies. Led by California utilities, EPRI is participating in an effort to determine the role that recently developed tools might play in planning for flexibility. EPRI continues to coordinate with industry groups, national labs, and utilities on the development of flexibility assessment metrics, as well as inventories of balancing resources.

Power System Planning Research Gaps Include:

Production cost tools with advanced algorithms can capture effects of variability and uncertainty in macro energy-environment-economic models as well as in power system operational models. These enable more accurate identification of flexibility shortages, which informs the design of remuneration mechanisms and, as a result, will influence future generation mixes.

ENHANCING FLEXIBILITY: CUSTOMER BEHAVIOR AND ENERGY UTILIZATION

What if electricity demand could be modified to match more closely supply availability, especially when supply cost is the highest? This would reduce the need for flexible supply resources. As supply changes, so would demand in a countervailing manner. Demand response refers to those customer actions that have the same effect of balancing the system as supply resources.

Energy efficiency permanently reduces a customer's load profile, benefiting the system through reduced demand and energy, but this effect can to be turned off and on at will, so it does not contribute to flexibility requirements.

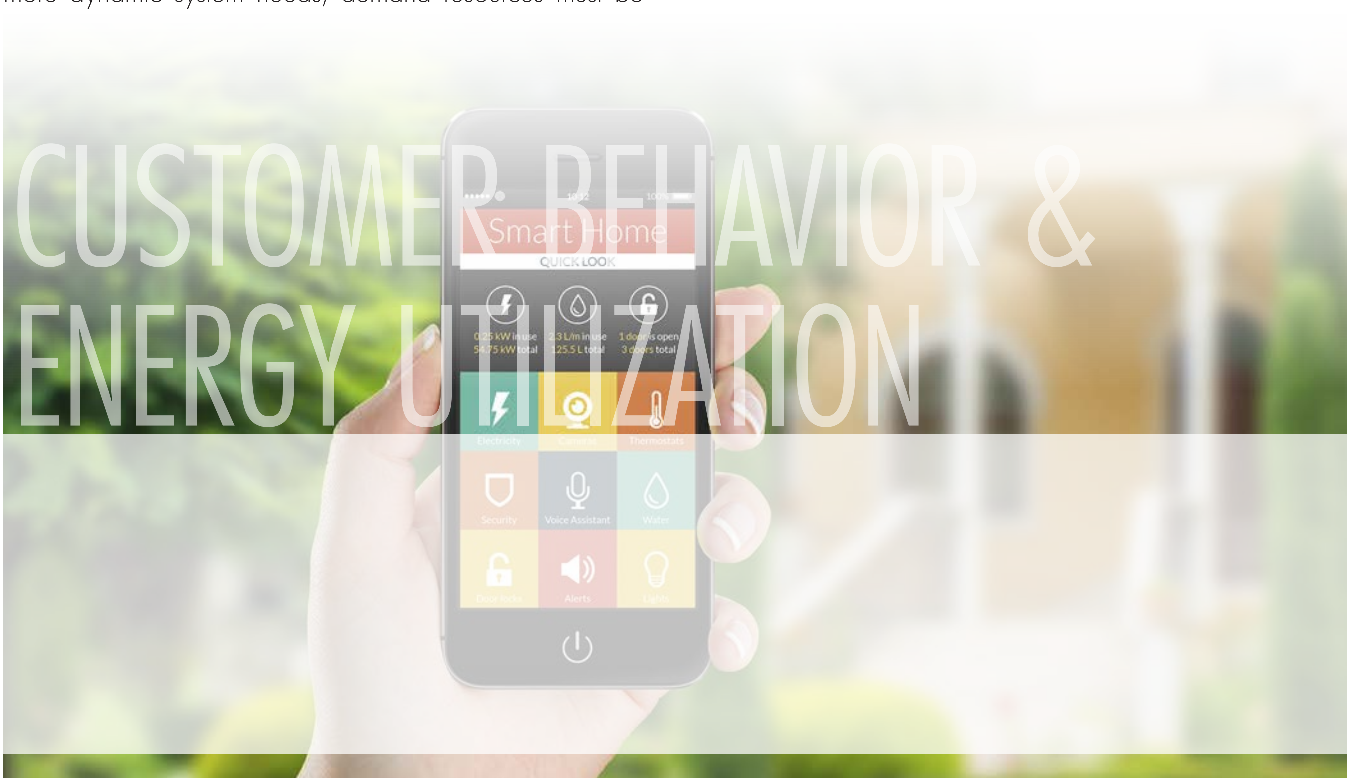
Conventional price and demand response involves sending prices, or managing load directly, to induce a change in electricity demand for a specified period. This change in use is effected only after notifying the customer of the action, often with advance notice, and only during specified periods and durations. Typically these interventions are invoked once per day. For example, ISO/RTO demand response programs are activated with at least one hour of advance notice, and in most cases are imposed for several hours only once per day. To provide flexibility that meets more dynamic system needs, demand resources must be developed that are available on very short notice for short periods several times a day.

Flexible demand response must come from customer loads that can be curtailed very quickly (i.e., under a minute or less) and that can be brought back on line relatively quickly and predictably. Alternatively, dispatchable distributed generation resources, especially those equipped with smart inverters and storage devices, can act in a way that serves flexibility needs—changes in demand that counteract variable supply resources.

Fast reacting loads can be provided from:

- Commercial buildings that use the building envelope and systems to absorb grid fluctuations
- Residences and small businesses that manage variability in buildings
- Industrial loads that can adjust quickly

Customer-side storage that could provide regulation and fast response includes building-integrated batteries, web-controllable HVAC and water heating systems, and plug-in electric vehicles with dispatchable charging capability.

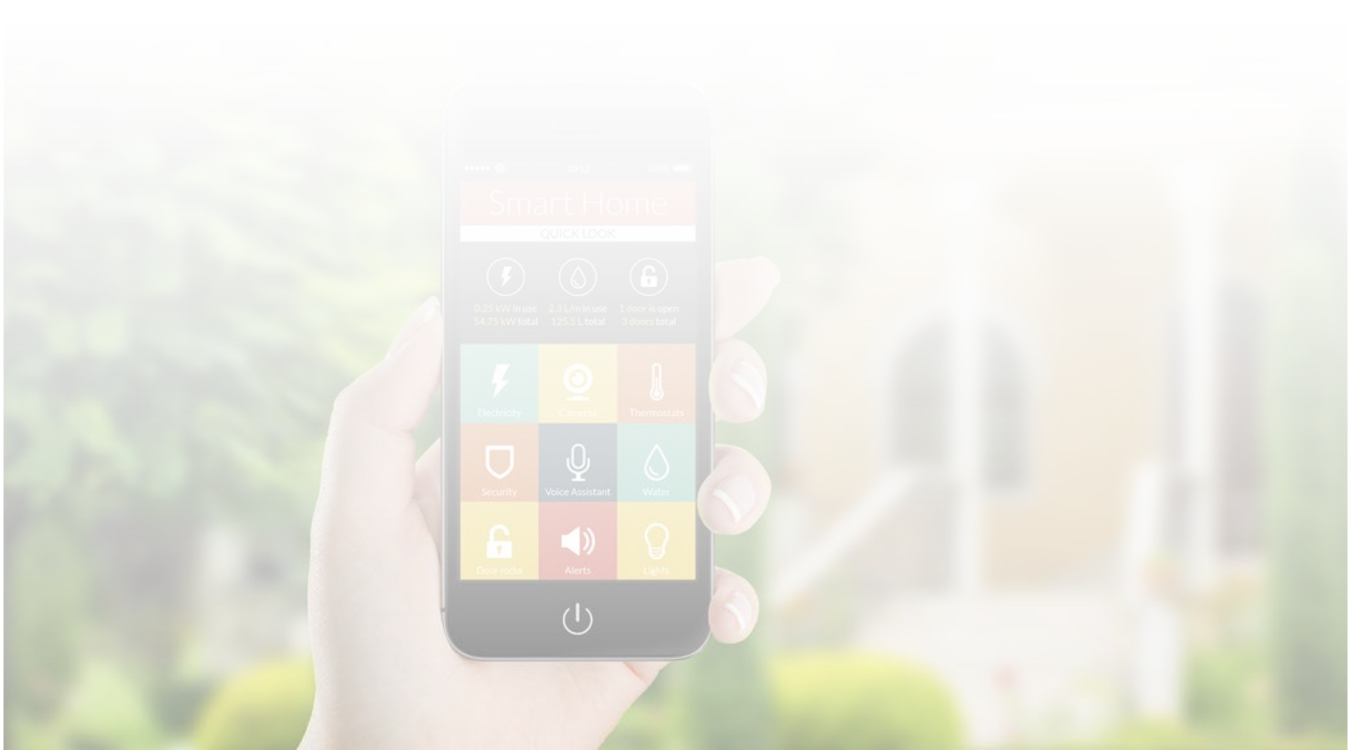


ENHANCING FLEXIBILITY: CUSTOMER BEHAVIOR AND ENERGY UTILIZATION

Current Research, Customer Behavior and Energy Utilization

EPRI is working to develop and test control technologies and strategies that can change end-use demand under the conditions required of a flexible resource. Research includes designing devices such as appliances and commercial electric equipment that can be shut off and turned on quickly without damaging the device, and in a manner acceptable to the consumer. This requires recognizing how the device serves customers and making its operation under controlled conditions acceptable. For example, controlling refrigerators to avoid food spoilage, water heaters to balance the system's need for control with the customer's need for hot water or a building's HVAC to maintain comfort. EPRI research is working to better understand how consumers use and value electricity so that demand response programs provide service commensurate with the payments the customer receives for participating.

ISOs/RTOs are developing opportunities for highly responsive loads to participate in the wholesale markets they operate. To use electricity demand as a resource, utilities need to understand the use of customer load as a flexible resource. Utilities need to be able to predict which customers will participate in various demand and price response programs, how they will respond to the offered inducements to change electricity use, and the persistence of those changes in electricity use over time. EPRI is addressing these needs, including predicting customer acceptance of demand response, in which the utility can control stipulated premise loads and price response, while customers change use in response to price signals. The latter research includes investigating the value of technologies that allow customers themselves to remotely change device loads. Additional research is focused on quantifying the benefits customers realize from price response program participation—an essential element to predicting program participation, performance, and persistence.



INFORMING SOCIETY'S CHOICES

In addition to technological change, policy choices and social preferences drive the need for increased flexibility in the electric system. The technology options and integrative analyses suggested here as steps to explore how a more flexible system could work can also be used to inform policy choices, balancing potential benefits of system flexibility with its cost.

The Future Power System: Flexible, Resilient and Connected

In addition to flexibility, resiliency and connectivity define fundamental attributes of the future power system and frame many of the major challenges and research opportunities facing the electricity sector. White papers covering power system resiliency and connectivity are also available to guide the discussions and decisions that will shape that research.

Connectivity

Connectivity refers to the increasingly widespread deployment of advanced communications and monitoring equipment, providing access to data streams and functionality that can inform decisions and behavior from the power plant to the end-user. Connectivity includes making utility data available to customers and their agents (primarily premises-metered data), and fostering the development of device and premises control technologies that enable customers to control load at anytime from anywhere. One promising avenue is testing the Open Automatic Demand Response (OpenADR) standard, which defines a standard for sending signals to equipment to curtail and resume operation as dispatched by a system operator. Standardizing communication protocols ensures that devices designed to be highly responsive can be used in any market, regardless of who designs the device's response.

Resiliency

Resiliency is the ability to harden the power system against—and quickly recover from—high-impact, low frequency events. Extreme weather such as U.S. hurricanes Katrina and Sandy and the Tohoku earthquake and tsunami in Japan demonstrate the need for resiliency. Other threats include tornadoes, wildfires, and severe geomagnetic disturbances.

INFORMING SOCIETY'S CHOICES

The 2013 vandalism that damaged several high-voltage transformers in a west coast substation focused the industry's attention on the need for enhanced physical security and resiliency against such attacks. The wide deployment of communication nodes in the grid raises concerns of cyber-related attacks. Coordinated cyber/physical attacks are of growing concern. Increasing dependence on natural gas-fired power generation can pose vulnerabilities if natural gas pipeline delivery is interrupted. Increasing dependence on wind generation can pose vulnerabilities if disrupted by a variety of causes.

Economic and social impacts of power system outages include financial impacts on asset owners and the broader community, ranging from small business owners to large corporations that rely on the grid. Society's rapidly growing dependence on digital technology increases consumer reliance on electricity, and reduces their tolerance for even brief outages. All of these are exerting greater pressure on utilities to enhance power system resiliency.

To achieve this, it is necessary to develop and deploy technologies that can address larger and more diverse, challenging, and frequent events. Enhanced power system resiliency will be based on three elements: damage prevention, system recovery, and survivability.

- Damage prevention refers to the application of engineering designs and advanced technologies that harden the power system to limit damage.
- System recovery refers to the use of tools and techniques to quickly restore service as soon as practical.
- Survivability refers to the use of innovative technologies to aid consumers, communities, and institutions in continuing some level of normal function without complete access to their normal power sources.

ACRONYMS

ABS	ammonium bisulfate
AEO	Annual Energy Outlook
AGC	automatic generation control
APC	active power control
CEMs	continuous emission monitors
CHP	combined heat and power
CO_2	carbon dioxide
CPUC	California Public Utility Commission
CSP	concentrating solar power
DER	distributed energy resources
DERMS	distributed energy resources management system
DMS	distribution management system
DOE	US Department of Energy
EIA	Energy Information Administration
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
ESIC	Energy Storage Integration Council
ESP	electrostatic precipitator
ESVT	energy storage valuation tool
EU	European Union
FACTS	flexible AC transmission system
FGD	flue gas desulfurization
HAPs	hazardous air pollutants
Hg	mercury
I&C	instrumentation and controls
IGCC	Integrated gasification combined-cycle
ISO	independent system operator
MATs	mercury and air toxics standards
NO_X	nitrogen oxides
NPPs	nuclear power plants
NREL	National Renewable Energy Laboratory
Polygen	polygeneration
PRA	probabilistic risk assessment
PV	photovoltaics
PWR	pressurized water reactor
RICE	reciprocating internal combustion engine
RPS	renewable portfolio standards
RTO	regional transmission organization
SCADA	supervisory control and data acquisition
SCR	selective catalytic reduction
SO_2	sulfur dioxide
TES	thermal energy storage
TSO	transmission system operator
URD	utility requirements document
wFGD	wet flue gas desulfurization

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