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TRANSMISSION TECHNOLOGY RESEARCH FOR RENEWABLE INTEGRATION

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PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The Energy Research and Development Division conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

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- Transportation

Transmission Technology Research for Renewable Integration is the final report for the Transmission Technologies for Renewable Integration Research project (contract number 500-99-013, BOA-192 conducted by CIEE. The information from this project contributes to Energy Research and Development Division's Energy Systems Integration Program.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

ABSTRACT

California has established aggressive Renewables Portfolio Standard goals to increase the amount of electricity generated from renewable energy resources. Thirty-three percent of California's electricity is required to come from renewables by 2020. Most of this new renewable generation will require the electric grid for delivering the electricity to customers. Renewable generators will be integrated into the electric grid at both the transmission and distribution levels. Most of them are expected to connect to the transmission system in locations remote from load centers and existing transmission infrastructure and will require transmission extensions. Some of this renewable generation will exhibit properties quite different from traditional generation and loads, which poses special challenges for providing adequate grid delivery capacity and maintaining reliability.

Meeting these challenges for successfully integrating renewables into the electric delivery system will require new or expanded capabilities for the grid and conventional "build" solutions alone will be inadequate. New transmission technologies offer the potential to provide a substantial portion of these new or expanded capabilities. This project assessed the technology research and development necessary for achieving an electric transmission infrastructure functionally capable of integrating the renewable generation capacity required to meet the Renewables Portfolio Standard goals of California.

Keywords: Transmission technology, emerging technologies, transmission research, renewable integration

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Introduction

Renewable resources within California are extensive and varied, and California has established aggressive Renewables Portfolio Standard (RPS) goals to increase the fraction of electricity made from renewable energy resources and to decrease greenhouse gas emissions. Thirty-three percent of California's electricity is required to come from renewables by 2020. This new generation will be integrated into the electric grid at both the transmission and distribution levels, but most of it is expected to connect to the transmission system in locations remote from load centers and existing transmission infrastructure and will therefore require transmission extensions. Some of this renewable generation will exhibit properties quite different from traditional generation and loads, which poses special challenges for providing timely adequate grid delivery capacity, maintaining reliability and avoiding economic inefficiencies. The addition of significant amounts of remotely located power will add to the loading on many transmission lines, which may not be capable of handling the additional load. Power flow constraints through transmission "gateways" into population centers must be relieved before the electricity from renewables can reach customers. The successful integration into the electric grid of the renewable generation required to meet California's RPS goals needs coordination among many public and private sector stakeholders in the renewable and electric grid communities. New technologies will also be required to provide the functional capabilities required for success.

Project Purpose

The purpose of this project was to identify emerging transmission technologies that could enable new or expanded transmission capabilities for the integration of the renewable generation required to meet California RPS goals and to determine the performance gaps and the research and development (R&D) required to close them.

Project Results

Transmission must achieve three broad objectives to successfully integrate renewables into the grid:

(1) Provide physical access for each new renewable power plant.

(2) Reliably accommodate any unique renewable generator behaviors, especially intermittency.

(3) Increase the existing system's power carrying capacity.

Expanded or new transmission capabilities derived from new and emerging technologies will become increasingly important as the penetration of renewables increases since the conventional "build" solutions alone will most likely prove to be inadequate or more expensive as a means of achieving these three objectives. These technologies can be classified into three broad categories: infrastructure, real time systems operation, and transmission planning and uncertainty analysis. Specific technologies in each class were described in this report, along with the gaps in the technology development and the research needed to fill the gaps.

The process used in this project linked technology development needs to product development. The "products" were the new technology systems or platforms that would be deployed to enable the new transmission infrastructure capable of integrating the renewable generation required to meet California's RPS goals. The new functions or capabilities required of this new transmission infrastructure defined the new technologies required.

A situational analysis identified the primary drivers as the forces outside the transmission system that influenced the manner in which renewable generation could be integrated into the grid. These included RPS policies such as Senate Bill 1078 and Senate Bill 107; Assembly Bill 32, the Global Warming Solutions Act; air quality and potential "once through cooling" (OTC) restrictions for thermal power plants; regulatory and permitting processes; locational constraints on renewables plants; and intermittency and other unique characteristics of renewables generators. Current transmission system constraints were also identified, including physical limitations imposed for reliability considerations and power market functioning and economic constraints.

The study also showed that transmission must achieve three broad objectives for the successful integration of renewable generation and will need expanded or new capabilities for achieving those objectives: (1) access to transmission; (2) accommodation of renewable energy characteristics; and (3) increased transmission capacity.

Acquiring new right of ways (ROWs) and building new transmission lines between renewable power plants and interconnection points on the transmission grid will be necessary. The new transmission capabilities required were enhanced acceptability of its physical presence and improved clarity of the costs and benefits of new transmission lines.

Some types of renewable generation exhibited variability and intermittency in performance that must be accommodated by the grid. New capabilities were required to address fast ramping, dynamic response, generator unit coordination, excess capacity, minimum load and market participation.

The transmission system had physical limits on the amount of power that can be transmitted. The new capabilities required included relaxed operating limits on static thermal and transient dynamic and voltage stability ratings as well as improved transmission expansion planning capability.

Three types of technologies were identified for achieving these new and improved capabilities: (1) infrastructure technologies; (2) real-time systems operation technologies; and (3) transmission planning and uncertainty analysis tools.

Infrastructure technologies were hardware devices, equipment and systems deployed in the physical transmission system to increase power flow capacity, control the flow of power, store energy, provide ancillary services, sense and communicate information about physical conditions, improve performance and protect infrastructure assets and human life. These technologies included but are not limited to: real-time rating (RTR) systems; new overhead line and conductor designs; underground transmission systems; high-voltage direct current (HVDC) transmission and storage superconducting devices; and power flow control devices, including fault current controllers.

Real-time systems operation technologies used advanced sensors, data communications, analytical software and computer visualization methodologies to enable system operators and ultimately automated system control to improve the performance of the transmission system in real time and over a wide area. An emerging key technology was the phasor measurement unit (PMU), an electronic device that measures precisely time-coordinated values of voltage and current over a wide area of the grid. When used in a network PMUs enabled unprecedented capabilities for enhanced system situation awareness and operator decision support and actionable options. PMUs can enable advanced applications such as rapid disturbance detection and alarming for the entire interconnection, diagnosis and compliance monitoring, real-time congestion management and intelligent grid protection. Other key real-time grid operating technologies included wind and solar ramp forecasting, smart grid outage islanding and restoration and real-time optimized operating nomograms that can mitigate capacity derating of key transmission pathways using conventional voltage and dynamic stability control options as well as new power flow control, energy storage and promising demand response options.

Transmission planning and uncertainty analysis tools can be used by system planners, transmission owners, regulatory and other stakeholders for making transmission design, siting, long-term deployment and construction decisions. Accurate, informative, user-friendly and fast power system analysis and optimization models were essential for ensuring the reliable and economic planning of the western regional power grid in support of RPS goals. Key areas where improved tools were needed include dynamic modeling of new renewable generators and improved dynamic modeling of system loads, especially in the near term to address the integration of residential and commercial photovoltaic (PV) systems and the dynamics of new residential air conditioners. New probabilistic forecasting methods and extreme event analysis were needed to deal with uncertainty in transmission expansion planning and congestion management. Accessible tools for the presentation of information and analysis for all stakeholders in the permitting and siting decision making processes were needed to speed up the construction of new acceptable transmission infrastructure.

This study identified about a dozen new and expanded transmission capabilities, which at a minimum could make renewable integration easier and less costly. The researchers concluded that at some higher renewable penetration level these expanded transmission capabilities will probably be required to achieve California's renewable energy goals in conjunction with the traditional "build" solutions.

The list of candidate new technologies identified in this study for realizing each capability is long and the cost of the research, development and demonstration (RD&D) needed to close every technology development gap found would be substantial and would require the coordinated efforts and resources of the private and public sectors at local, regional, national and perhaps international levels. The researchers believed that priorities need to be established to select which technologies could enable the most valuable capabilities for integrating renewables, to identify the resources and institutions that need to be enlisted in the efforts and to determine when the desired results were needed.

The general types of transmission technologies that RD&D programs might want to consider in the context of new or expanded capabilities included:

- Technologies for providing access to the grid that should reduce the visual profile and other environmental and siting impacts, of a transmission line and perhaps other grid infrastructure. They should also help the public and other concerned parties and decision makers better understand and communicate the economic and strategic value and costs of various alternatives.

- Technologies that mitigate intermittency impacts, help operators prepare for and react to problems and help buffer or forecast the variable behaviors.

- Technologies that remove operational and reliability constraints and those that allow higher current or power flows on lines or paths.

- Technologies for improved planning and forecasting to address growing complexities and uncertainties.

Project Benefits

This study identified emerging transmission technologies that could enable new or expanded transmission capabilities for the integration of the renewable generation required to meet California RPS goals. The study also identified performance gaps and the R&D required to close them. Increased integration of renewables into California's electricity system will help reduce greenhouse gases that contribute to climate change and will also reduce other air emissions that cause air pollution.

CHAPTER 1: Introduction

1.1 Background

Renewable resources within California are extensive and varied, and California has established aggressive RPS goals to increase the fraction of electricity made from renewable energy resources and to decrease greenhouse gas emissions under AB 32. By 2010, 20 percent of California's electricity is required to come from renewables, and by 2020, 33 percent is proposed. This new generation will be integrated into the electric grid at both the transmission and distribution levels, but most of it is expected to connect to the transmission system in locations remote from load centers and existing transmission infrastructure, thus requiring transmission extensions. Some of this renewable generation will exhibit properties quite different from traditional generation and loads, which poses special challenges for providing timely adequate grid delivery capacity, maintaining reliability, and avoiding economic inefficiencies. The addition of significant amounts of remotely located power will, regardless of any unique characteristics of this additional power, add to the loading on many transmission lines, which may not be capable of handling the additional load. Finally, power flow constraints through transmission "gateways" into population centers must be relieved before the electricity from renewables can reach customers. We refer collectively to these challenges as Renewables Integration (RI), and it is often cited as the major barrier to achieving the renewable goals of the state.

The renewable resources for larger, central station renewable power plants tend to be located remote from load centers and other generation resources, and therefore are remote from the existing electric transmission lines. For example, the Tehachapi region is rich in wind resources, but remote, and its existing transmission capacity is inadequate for delivering the projected amounts of electricity generated to the customers. Likewise, the substantial geothermal resources in the Imperial Valley and the concentrating solar resources in the Mojave area present similar transmission access problems. Expansion of new transmission capacity is expensive and often takes many years getting siting approved. Given the relative short construction times for many types of renewable generation, having transmission available when the power plant is ready to make its contribution toward meeting the renewable goals is problematic and threatens the ability to meet the state's renewables goals. Furthermore, adding new generation without upgrading existing transmission capacity or adding new, can result in more economic inefficiencies such as higher congestion costs for consumers.

At the other extreme, some of these renewable generators will be located, and integrated into the grid, near or at the electric loads. Prime examples are photovoltaic panels mounted on building roof-tops, and small biomass-fueled generators located at the community level. These "distributed" generators, in contrast to "central station," are usually connected at the distribution level, which in general was not designed to connect generation resources of any kind, and can cause some safety and operational issues. And while some of the power from a distributed generator might be fed to a neighboring load by the grid, some, if not most, of the power will be consumed locally, creating an ambiguous role as a new kind of generator and a negative load, at least from a transmission perspective.

From a transmission operational dynamics perspective, geothermal and biomass energy are similar to traditional power generators, especially base-load, and therefore do not pose much concern about their operational behavior within the power grid, though some biomass resources vary seasonally. Some types of renewable generation, however, are "fueled" by variable, or intermittent, energy sources like wind and sunshine, i.e., insolation, which are controlled by weather and rotation of the earth. These intermittent renewables can create renewable energy power plant behaviors for which the grid was not designed and that are quite unfamiliar to grid operators and outside their control. To achieve a 20 percent renewable energy content will require a projected renewable nameplate capacity of over 14,000 MW (which represents about 8,000 MW above the 2006 recorded capacity of about 6,000 MW), with more than 60 percent of that capacity coming from the intermittent renewable forms of wind and solar. To achieve 33 percent would require 26,000 MW of renewable nameplate capacity (20,000 MW above the 2006 recorded capacity.) Relatively small penetrations of intermittent renewables are expected to have "operational implications significant but manageable" ("California Independent System Operator Integration of Renewable Resources," David Hawkins & Clyde Loutan, Cal ISO, November 2007). For greater penetration levels, however, transmission infrastructure expansion, improved wind and solar forecasting, increased ancillary services for the grid, and new technologies for a smarter grid will likely be required. Energy storage might also be deployed to mitigate some of the effects of intermittency.

Not all the news associated with increased use of renewable generation integrated into the grid is negative. In addition to the obvious reduction in greenhouse gas reductions, inherent in renewable generation is a hedge against volatility in fuel prices and reliance on imported fossil fuels. Certain renewable resources, such as solar, have a reasonably strong correlation with load temporal profiles in California, and therefore might help with meeting peak load demands, and, especially for distributed forms, reducing congestion costs, deferring grid infrastructure investment and perhaps providing local voltage support. The non-intermittent renewable resources, such as geothermal and biomass, of course can add to a growing need for baseload generation capacity. Proper integration among renewable resource types and across geographical regions might further enhance renewables contribution to a stable, reliable and affordable grid.

The successful integration into the electric grid of the renewable generation required to meet state RPS goals needs coordination among many public and private sector stakeholders in the renewable and electric grid communities. But new technologies will also be required to provide the functional capabilities required for success.

The purpose of this research study was to produce a technology development survey for achieving an electric transmission infrastructure functionally capable of integrating the renewable generation capacity required to meet the renewables goals of California. The process used linked technology development planning to product development. For this research, the "products" were the new technology systems or platforms deployed in the new transmission infrastructure capable of integrating the renewable generation required to meet the California renewables goals and somewhat beyond. Applying the design strategy that form follows function, the functions or capabilities required of this new transmission infrastructure defined the new technologies required. The technology development required to close the "gaps" for these new technology "products" needed to achieve the required functionalities or capabilities were identified and mapped as short, mid, and long term milestones.

1.2 Project Objectives

Project objectives were to:

- Determine New Technologies for the Future Transmission Infrastructure for Successful Renewable Integration
- Identify Technology Development Gaps and Milestones
- Produce the Renewable Integration Technology Development Report and Presentation

1.3 Project Approach

The research for this project was conducted through three different means.

- Published and unpublished papers resulting from prior studies on related subjects. The direct or indirect involvement of the authors in a number of these studies facilitated this research.
- Meetings with knowledgeable representatives from various stakeholders. A full day meeting was held on July 22, 2008 with representatives from two of the three California investor-owned utilities, Cal ISO, the CPUC, and the Energy Commission.
- Interviews with key industry and government research personnel as well as other stakeholders involved with the transmission grid.

1.4 Reporting Approach and Structure

The problem of renewable integration can be considered as three separate, but interrelated issues:

- **Access –** Many of the new renewable resources will be located away from suitable interconnection points in the existing transmission grid and will require the construction of new transmission lines.
- **Accommodation –** Some renewable resources, especially wind and solar, exhibit intermittency and other dynamic characteristics which the grid is not well suited to accommodate.
- **Capacity –** Additional remote energy resources will increase the loading on much of the transmission grid. A large fraction is believed to be unable to handle the increased load without an expansion of available capacity.

This report examines each of these overall issues and defines a general set of new or expanded capabilities that will be needed for renewable integration associated with each issue. It then discusses each of the technologies which could be used to obtain these new capabilities. Since most of the technologies are not fully commercialized and available, the "gaps" or areas where further research is needed to have full access to the technology. Finally, these gaps lead to the research needed for each technology to fill the gaps. The authors do not expect that the PIER program or any single agency is likely to attempt to sponsor research to fill all the gaps, nor that every technology will prove to be economically or technically viable. In some cases, where there seems to be general consensus among the various industry experts, conclusions about the importance of particular technologies will be stated, although this should not be taken as recommendations of specific projects.

For clarity, the technologies are divided into three general categories: infrastructure, real time grid operations, and forecasting and planning. Recommended research is organized into short term (2009 – 2012), medium term (2013 – 2020), and long term (2021 – 2030). This is intended to provide a timeline consistent with the renewable deployment goals of 20 percent around 2010, 33 percent by 2020, and perhaps 50 percent by 2030.

To assist in characterizing the degree of maturity of a developing technology this report will use the "stages and gates" definitions and terminology used by the Energy Commission:

- Stage 3: Research and Bench Scale Testing (Gate 3 Objective is Proof of Feasibility)
- Stage 4: Technology Development and Field Experiments (Gate 4 Objective is RD&D Product Development Initiation)
- Stage 5: Product Development and Field Testing (Gate 5 Objective is RD&D Demonstration Initiation)
- Stage 6: Demonstration and Full- Scale Testing (Gate 6 - Market Transformation Initiation)

For those wishing background information on terms and the operation of the power grid, Appendix 1 Grid 101, Basics of Grid Engineering Principles, has been included.

CHAPTER 2: Situational Analysis

Concerns about global warming and resource constraints are stimulating dramatic changes in energy policy. RPS regulations have mandated that by 2010 electricity used in California will be generated 20 percent from renewables. A goal of 33 percent by 2020 has been recommended in AB32 and future requirements could extend this to a 50 percent renewable content. The addition of significant renewable content to the grid impacts the transmission system in a variety of ways. Historically, new plants have been sited based in large part on access to the transmission system. In contrast, renewable power plants will be built where the required natural resource (solar, wind, geothermal, etc.) is available in abundance. Many of these sites will require new or upgraded transmission lines. Sun and wind, the primary renewable resources, are both intermittent. These characteristics of most electric generation "fueled" by renewable energy create challenges which will need to be met by adding to or improving the capabilities of the transmission system.

The overall situation is complicated by the current and projected status of the grid over the next few years, even without considering the addition of renewables. Much equipment is aging and planned to be retired during the next 10 years. Prospective once-through cooling regulations may accelerate this trend. Operating margins have been steadily shrinking as transmission investment has not kept pace with increases in demand. Dynamic operating constraints have emerged which prevent major transmission lines from operating at the levels for which they were designed. Increasing levels of imported power have led to a substantially larger, more interconnected regional grid than envisioned when much of the infrastructure was planned.

The primary drivers of change are those external policies and market or technical forces outside the control of the transmission system stakeholders. These policies and market forces encourage the application of current technologies and the development of new technologies or the expansion of capabilities of current technologies. These, in turn, encounter technical, economic, or policy constraints which become the second level of drivers that determine the selection of from among the available choices of new or expanded technologies.

2.1 Primary Drivers

These are the forces outside of the transmission system which will exert major influences on the integration of renewable energy into the grid. They consist of policy drivers from various regulatory bodies and physical constraints imposed by the nature of renewable resources.

RPS Policies

The primary policy drivers are SB 1078, which established a 20 percent RPS goal for 2017; SB107, which accelerated that goal to 2010; and AB32 which, while not legally mandating it, effectively added a requirement of 33 percent by 2020. It appears that levels of renewable penetration even beyond 33 percent may be in California's future, possibly as much as 50 percent by 2030. Renewables, for the purpose of these policies, are defined as those power sources under the control of utilities and, as such, do not include distributed generation installed by end users in a net metering program.

In 2007, renewable resources accounted for 11.8 percent of California's electrical energy sources[1]. Projections from an April, 2008 Cal ISO briefing indicate that to meet the RPS goals, about 10,000 MW of renewable power will need to be added by 2010, 20,000 MW by 2020, and as much as 37,000 MW by 2030 if a 50 percent renewable target is implemented[2].

Renewable Locations

In the past, new power plants have tended to be located near existing transmission lines. Renewable energy resources, however, must be located where the resource is available. Thus geothermal, wind, and solar power will all be located where there is an ample supply of the desired resource. These locations are typically in areas remote from load centers and underserved by transmission infrastructure. Thus, significant new transmission lines will be required to provide access to increased renewable energy sources. Various stakeholders have come together for the Renewable Energy Transmission Initiative (RETI) to attempt to determine logical corridors for new transmission that can serve multiple projects.

Siting Process Lead Time

The current process for new transmission siting is highly complex, with diverse stakeholders and jurisdictions, and no integrated process for generation and transmission planning. As a result, new transmission lines typically require considerably more lead time than new generating plants.

Intermittent Power

Renewables present unique challenges to a market based energy system. Wind and solar are intermittent, that is, they are available only during certain periods and, during these periods, available power can vary significantly. The availability of solar power is reasonably consistent with the typical load profile in that peak generation during hot summer days coincides with peak power demands. Wind, however, is primarily a night time resource, maximizing generation capability during periods of lightest load. Cal ISO projections indicate that there will be periods where available wind generation exceeds total demand.

2.2 Current System Constraints

These are the forces within the transmission system that will constrain or influence the selection of methods to satisfy the primary drivers. They are primarily technical constraints imposed by

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[1] California Energy Commission, *Net System Report 2007*, Table 2, pgs 4-5

[2] Budhraja, Vikram, John Ballance, Jim Dyer, and Fred Mobasheri (Electric Power Group, LLC), Eto, Joseph (Lawrence Berkeley National Laboratory). *Renewable Resource Integration Project – Scoping Study of Strategic Transmission, Operations, and Reliability Issues*, PIER Final Project Report MR-047 California Energy Commission, PIER Energy-Related Environmental Research Program. Publication #CEC-500-2008-081. Pg 8 Table 6 http://www.energy.ca.gov/2008publications/CEC-500-2008-081/CEC-500-2008-081.PDF

the physical nature of the transmission system or market constraints imposed by the need to operate within the energy marketplace.

2.2.1 Market and Cost Constraints

- ***Market Operation*** **–** Energy markets today are designed to operate on a contracted basis, i.e. a supplier contracts to deliver a specified amount of power in one of several markets: day ahead, hour ahead, 5 minute ahead. There are substantial penalties for either over- or under-production. These penalties create severe problems for participation of intermittent resources. To overcome these, Cal ISO has instituted the Participating Intermittent Resources Program (PIRP) which is intended to allow market participation of intermittent resources. Currently, although the Cal ISO is planning on integrating solar, it is primarily wind which is eligible for this program, and wind farms which supplement the energy produced with non-renewable back up resources are not eligible for this program[3].
- ***Minimum Load*** **–** In many cases, the available output of power plants cannot be reduced and must be purchased, either for technical reasons, such as in nuclear plants, or for contractual reasons that were necessary to make the power plant economically viable. The renewable plants are expected to be in this "must take" category. This leads to the so called "minimum load" problem, which occasionally occurs even today. This is the problem of having more generation than load, usually occurring at night. As available wind tends to be higher at night, this problem is expected to increase as larger amounts of wind power are integrated into the grid.
- ***Excess Total Generation*** – To achieve the increasing percentages of renewables, a rapid addition of renewable power plants will be required. The needed rate of addition is considerably higher than the growth of demand and is projected to be higher than the sum of demand growth and the retirement of existing equipment. In other words, the addition of the renewable plants may force the retirement or lowered use of some existing thermal plants, even though they are still viable. Cal ISO forecasts 13 percent less non-renewable generation in 2020 than in 2008[4].
- ***New Regulation/Ramping Resources*** – The addition of increasing amounts of new renewable generation will increase the need for fast-response controllable generation sources for frequency regulation, voltage regulation, and fast ramping. While some of these services could be provided by generating units that would otherwise be deactivated (see Excess Total Generation, above), the likelihood is that some or most of those units would be unsuitable for such duty. The new resources envisioned would be fossil-fired combustion turbines, storage systems, demand response, interruptible load, etc.

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[3] CAISO Issue Paper *Integration of Solar Energy into the Participating Intermittent Resource Program (PIRP)* Revised 4/17/2008, pg 2.

[4] Budhraja, et al, pg 8

- ***Predictability*** – The ability to commit to deliver a specific amount of energy is dependent on the accuracy of wind and solar forecasting, whether day ahead, hour ahead, or 5 minutes ahead. The intermittent nature of solar and wind resources makes it difficult for them to fully participate in energy markets.
- ***Congestion Costs*** – Once connected to the grid, remotely located resources must be brought into major load centers. Lines which currently have adequate capacity are likely to experience increased periods of congestion.
- ***Ancillary Service Costs*** – Increased costs for ancillary services are expected due to the characteristics of some intermittent renewables, such as wind and photovoltaics. Conventional generators have high inertia, leading to relatively slow changes in output. In contrast, wind and solar have relatively little to virtually no inertia and can respond quickly to changes in solar insolation or wind speed. This leads to the need for increased short term ramping capability and regulation services.
- ***Other Costs*** – Load following is the ability of the grid to respond to changes in the load over time, in particular to the daily variation of load. Typical loads have well characterized morning increases in power requirements and decreases in the evening. Grid resources have long been optimized to handle this. However, wind resources tend to follow the inverse of that characteristic, leading to the need for additional resources to compensate for this characteristic. These resources add to the cost of operating the grid but do not increase capacity.

2.2.2 Technical Constraints

Major technical drivers or constraints arise not only from the unique characteristics of renewable sources, but also from the addition of different classes of equipment with static and dynamic characteristics different from what operators and planners are accustomed to. Reliability is a vital operational issue for the grid, which can either increase the risk of outages or costs associated with mitigating the risks. The intermittent behavior of most renewable generation implies higher costs or greater reliability risk.

For those wishing to better understand some of the technical issues involved, a primer on the basic electrical engineering principles relevant to grid operation are offered in Appendix A: Grid 101, Basics of Grid Engineering Principles.

- ***Inertia*** – Inertia is the physical property of an object which causes it to stay in motion, once started. Thermal and hydro power plants, the mainstay of electric energy production, around which the transmission grid has developed, all utilize massive rotary generators which have large amounts of inertia. This property tends to stabilize the grid in the event of a disturbance. Wind and solar power plants have less or little inertia and tend to react much more rapidly to disturbances. Unless compensated for, lack of inertia can contribute to grid instabilities.
- ***Stability*** – Over wide areas, the grid can exhibit unstable behavior if power flows exceed dynamic limits. If not controlled, this can trigger large scale outages. This dynamic grid stability, even without the addition of renewable resources, is a critical issue. To maintain reliability, potential instabilities must be sensed and responded to quickly.

While transmission lines have a designed power handling capacity based on thermal limits, instabilities frequently limit maximum transmitted power to levels significantly less. In particular, this limits both the amount of power which can be imported from out of state and amounts which can be transferred from one part of the state to another. The addition of significant remote generating facilities, much of it with low inertia, may have undesirable effects.

- ***Import Constraints*** – In 2007, California imported 92,000 Gigawatt Hours (GWhr), about 30 percent of the total power of 302,000 GWHr used.[5] Much of this was during summer peak usage periods. During these periods, major interstate transmission lines typically operate near their maximum allowable power transmission. The limits on transmission are typically well below thermal limits to allow for N-1 contingency planning. However, they often are restricted to even lower values due to stability constraints. As a result, the current ability to import higher levels of power from out of state is extremely limited. Increases in imported renewable power, if available, will come primarily by comparably reducing other types of power.
- ***Local Area Limitations*** – Within the state, it appears that much of the new renewable energy will be generated in remote areas, while most of the consumption will be concentrated in the population centers such as the Los Angeles Basin. Five load centers comprise 87 percent of the total load in California. Power flow transmitted into these areas is channeled through key substations called gateways. Many of these gateways are already operating at their limits, which is typically in the range of 50 percent of the locally consumed power.[6] If the gateways to an area are limited to 50 percent of the consumed power, then the balance of the power must be generated within the local area. As a result, even if there is abundant renewable power generated within the state and connected to the transmission system, many existing parts of the system will need significant increases in capacity.
- ***Limited Bulk Storage*** – Existing large storage facilities, which could act to shift loads from day to night, are extremely limited and may be constrained by transmission limits. The Helms Pumping Facility, one of the largest in the state, with a maximum pumping capability of 900 MW from 3 pumps, operated at this level less than 250 hours in 2005[7], primarily due to transmission constraints. New pumping facilities require 10 – 12 years to implement[8].
- ***Available Grid Control*** – The physics of electric power requires the actual power generated at any point in time exactly equals the amount of power consumed. If

[5] California Energy Commission, *Net System Report 2007*, Table 2, pgs 4-5

[6] Budhraja, et al, pg 12.

[7] *Integration of Renewable Resources, Achieving California's 20% Renewable Portfolio Standard,* CAISO, David Hawkins & Clyde Loutan, Principle Investigators - November 2007, pg 26

[8] *Integration of Energy Storage Technology in Power Systems* CAISO Web Conference Call May 29, 2008

generated power begins to exceed consumption, the voltage will rise so that loads consume more power. A similar effect happens when loads demand more than is available. The current state of grid functionality is that actual control of power flow is extremely limited. Power follows the path of least resistance and grid operators primarily exercise control by dispatching more or less power at appropriate locations to maintain the desired flow and to maintain voltage and frequency limits. While devices exist that can contribute control functions, these tend to be expensive and only used in very specific situations. Intermittent power sources generally complicate the problem of managing the grid.

- ***Real Time Wide Area Situational Awareness*** – As more power is transmitted over longer distances from more places, situational awareness of wider areas becomes ever more important. Systems that present real time wide area situational awareness are just beginning to become available as the technology of time synchronized measurements or synchrophasors becomes widely implemented.
- ***System Protection –*** Real time automatic control is highly desirable to protect the grid when an unexpected event occurs and rapid action is needed to mitigate the effects. Currently, this is largely limited to localized protection schemes intended to protect equipment rather than the grid. Increasing imports and longer transmission distances are adding to the need for more intelligent protection systems which can protect grid functionality as well as equipment. In many areas, the increased loading of transmission lines threatens to allow fault currents in excess of the availability of equipment to handle the faults. New technologies to limit these currents are in the demonstration phase.
- ***Extreme Events*** – Extreme events can be described as system disturbances characterized by multiple failures of transmission system components, resulting in widespread system collapse through cascading outages. Such large-scale events have always been difficult to analyze, plan for, and manage, but the potential severity of such events has grown with the interconnectedness of the grid, and is likely to grow more with the increasing integration of intermittent renewables in the system. Operators in adjoining systems generally don’t have good visibility of each other’s systems, hindering both the detection of impending or initiating extreme events, and effective countermeasures once an operator becomes aware an extreme event is propagating. Existing tools for operators have not been adequate to respond to these events. Currently there is significant effort focused on real-time system awareness and on-line analytical tools utilizing phasor measurements; additional areas of potentially beneficial research include advanced planning to better identify critical transmission paths, adaptive protection systems, and strategies for automated islanding of the grid.

CHAPTER 3: The Role of New Technology in Renewable Integration

Because most new renewable power plants will be located in areas rich in renewable resources but remote from California electricity customers, electric transmission will be crucial for transporting the renewable electricity to load centers, and thus for meeting the state's renewable energy goals. Consequently, each new renewable power plant must be successfully integrated with the transmission system. To fulfill this mission, transmission must achieve three broad objectives: (1) provide physical access for each new power plant, (2) reliably accommodate any unique renewable generator behaviors, and (3) increase its power carrying capacity to handle the additional electric power flows.

It is reasonable to assume that modest penetrations of renewable generation, perhaps up to 20 percent, can be successfully integrated into the grid by traditional system investments, such as building new lines and conventional generation for increased capacity and to maintain reliability. However, as the penetration of renewables grows, to perhaps 33 percent and beyond, and more transmission infrastructure is added to the system, its complexity will grow along with operational difficulties. It also will likely become increasingly difficult to meet the environmental and economic criteria for siting new infrastructure in a timely manner, further reducing the effectiveness of the "build" approach. As an alternative, new technologies can be deployed in the transmission system to endow it with expanded or new capabilities that, at a minimum, will make renewable integration easier and less costly, and ultimately at some higher renewable penetration level, will probably be required to achieve California's renewable energy goals. Some transmission stakeholders have expressed the opinion that we are already at the level of renewable penetration in California where new technologies will be required.

3.1 Improved and New Capabilities

Each expanded or new capability, and its enabling new or emerging technologies, is generally described below in the context of addressing the challenges facing the achievement of each of the three broad transmission objectives for successful renewable integration.

3.1.1 Access to Transmission System

For most new renewable power plants, access to the transmission system can be directly translated into acquiring new right of way (ROW), and building new transmission lines between the power plant and an interconnect point on the transmission grid.

The siting process for new transmission project is highly complex and difficult, involves many different stakeholders, and takes many years, typically 10 to 12 years for a major line. While there are a number of state and national policy changes being pursued to shorten this time, concern remains that it will take longer to build the new transmission extension to a renewable power plant than it will to build the power plant.

Two major impediments to timely new ROW approvals are cost/benefit allocation economic debates, and siting challenges, exemplified by, "not in my backyard." Two improved capabilities the transmission community could use to accelerate new transmission projects are:

Access Siting Capability #1: To facilitate environmental and societal deliberations, and enhance acceptability of new transmission lines.

Some enabling new technologies: Hardware technologies that reduce the physical footprint or visual impact, such as underground and compact high current lines; public process techniques that facilitate environmental/societal issue definition and resolution, and stakeholder interactions.

Access Cost/Benefit Capability #2: To enhance clarity of project costs, and economic and societal benefits for new transmission lines

Some enabling new technologies: Techniques, methodologies and models that would bring science to bear on enhanced understanding and validity of economic and societal costs and benefits, their allocation among stakeholders, of new transmission line projects.

3.1.2 Accommodation of Renewable Energy Characteristics

From a transmission operational dynamics perspective, some renewable energy plants such as geothermal, biomass and perhaps solar thermal with enough thermal storage will benignly operate similar to traditional baseload thermal power generators. Wind and some solar renewable generation, however, are intermittent, and exhibit power plant behaviors unfamiliar to grid operators, and for which the grid was not designed.

Solar power characteristically ramps up in the morning and down in the evening with no night time output, but with a seasonable-variable power profile. Additionally, it has short term variations due to cloud cover. Solar photovoltaic generators use solid state invertors that exhibit little or no operating inertia so characteristic of conventional thermal generators with their large rotating mass, and therefore will react much more quickly to transients. Little is known about the effects of large penetrations of these low-inertia generators on the transmission system.

Wind power tends to be higher at night and is subject to short term variability from changes in wind. The dynamic behavior of wind generators is different from typical thermal generators, and there are significant differences between different types of wind turbines designs.

The Energy Commission Intermittency Analysis Project has projected that meeting the 33 percent goal by 2020 will result in power production capacity in excess of total demand requirements. Existing conventional plants would need to be closed or operated at lower capacity factors, potentially reducing the availability of system support generation. This situation might be compounded if coastal thermal plants using once through cooling must be shutdown.

Finally, to stimulate the private development of renewable power plants, utility contracts generally include the guaranteed acceptance of power generated, whether or not it is needed or is the most economical available.

There are emerging technologies that could provide new transmission capabilities to accommodate the special operating needs of renewable generators, and some of their system effects.

New Accommodation Ramping Capability #1: To reliably respond to rapid up and down power ramping.

Some enabling new technologies: Current ramping techniques include the ability to dispatch fast acting generators. These are typically gas fired, so increased use of current techniques will tend to dilute the beneficial effects of renewable resources, and have future electricity cost consequences. Equipment capable of delivering or absorbing power, such as energy storage, wind and solar forecasting techniques that project ramping needs, and perhaps some load management approaches might compensate or mitigate ramping requirements.

New Accommodation Power Market Capability #2: To enable intermittent renewables to participate in power markets on equal basis.

Some enabling new technologies: To maximize their economic return, renewable power plant developers need to sell power in the established power markets, both short term and long term. This requires a high level of generation predictability over short and longer-term time periods, or the ability to dispatch. Wind and solar forecasting techniques, market prediction techniques, and control equipment, such as storage, to control when power can be dispatched, should increase the market value of intermittent renewables.

New Accommodation Dynamic Behavior Capability #3: To operate the grid in response to renewable power plant dynamic behaviors.

Some enabling new technologies: The primary concerns around dynamic behavior are associated with the potential decrease of total system inertia leading to increased instabilities and the dynamic response of large wind farms. New generator modeling, analysis or forecasting tools related to these behaviors, or control equipment to mitigate the impacts of these dynamic behaviors are some technology candidates.

New Accommodation Excess Total Power Capability #4: To reliably take excess capacity.

Some enabling new technologies: The existence of excess total capacity requires that some existing system power plants be underutilized or closed. These will likely be older, less efficient plants, many that are located closer to load centers. This may create additional grid stability issues as power plants, on average, become located further from load centers. Planning tools, studies, and techniques could evaluate and mitigate both the economic and technical impact of plant closures, and tools and equipment, such as energy storage, could compensate for loss of grid support from these plants.

New Accommodation Minimum Load Capability #5: To economically and reliably take renewable power during times of minimum load.

Some enabling new technologies: If, as expected, wind power becomes the largest single source of renewable energy power, the minimum load problem is expected to become significant. Wind power tends to peak and night when loads are lightest. In combination with other sources of "must take" energy, such as nuclear power and power contracts, there are expected to be periods when total "must take" power exceeds demand. To avoid economic penalties, consumption could be increased during those periods. Planning and forecasting tools, and equipment for increasing or control load could be developed to provide this capability.

3.1.3 Increased Transmission Capacity

Any transmission line has physical limits on the amount of power that can be transmitted. Which limit is the dominant factor constraining the capacity of a given line at a given time depends on the conditions of that particular line and the broader wide-area transmission grid.

Because the technological sophistication of current situation monitoring capability is not particularly accurate or precise, conservative static operating limits have been set often far below the physical limits as an engineered safety factor, which is in effect a derating of the capacity of a line typically by 20 to 50 percent, or more.

There are two fundamental classes of limits, thermal and stability.

Thermal Limits: The maximum power a particular line can ever handle is its thermal limit. The primary source of heat comes from the interaction between the electrical resistance of the line material and the electric current flowing through it. Above this limit, a line may excessively sag, creating a safety hazard or an outage, or be physically damaged by excessive temperature.

Stability Limits: Poor voltage support, and dynamic and transient instabilities can result in even substantially lower capacity limits below the thermal limits in some situations. It is not unusual for a major interconnection path to be operationally limited by instabilities to half its rated static thermal limit. This effect imposes severe limits on the amount of renewable power which can be imported into California, and into major load centers within the state.

There are emerging technologies that could in principle provide the capabilities to reduce the margins of operating limits required for safety, and even raise the physical limits, thereby adding substantial "new" capacity without building new transmission lines. The capabilities would prove vital to meeting renewable energy goals if building all of the new transmission capacity needed falls short, especially likely in dense urban load centers, and might be preferred as a cheaper way to get greater transmission capacity.

New Capacity Thermal Capability #1: To raise static and physical thermal limits

Some enabling new technologies: New conductor materials with a higher thermal capacity, direct current (DC) transmission, or possibly superconducting cable could result in significant transmission capacity expansion, and dynamic (real time) "thermal" rating monitoring to relax static limit margins could produce incremental capability increases, all in the same or smaller environmental footprint.

New Capacity Voltage Stability Capability #2: To relax, or eliminate need for, voltage stability constraints.

Some enabling new technologies: New monitoring, evaluation and predictive analytic and modeling tools, e.g., optimized real-time nomograms, could improve situation awareness and permit smaller, better defined, constraint margins. New hardware, such as devices using advanced power electronics or energy storage, deployed locally, could provide voltage stability support.

New Capacity Transient Stability Capability #3: To relax, or eliminate the need for, transient stability limits.

Some enabling new technologies: Transient stability is the ability of the transmission grid to regain its equilibrium in the event of a transient disturbance, such as a line fault or generator trip. Time frames are typically milliseconds to seconds. Predictive off-line techniques, real time monitoring and analysis techniques could alert operators and automated systems, and new or improved methods or power electronic equipment could control for instabilities.

New Capacity Dynamic Stability Capability #4: To relax, or eliminate the need for, dynamic stability limits.

Some enabling new technologies: Dynamic stability is the ability of the transmission grid to regain its equilibrium over time frames of 1 minute to as much as 30 minutes. Problematic instabilities can manifest in a number of different behaviors, with low frequency oscillations being perhaps the most egregious in the Western grid as a reason for capacity deratings. Low-frequency oscillations, which cause power to surge back and forth through wide-areas of the grid, typically have a period of a few seconds and can build over periods of minutes to hours. They have been identified as the initiating event of some costly major multi-state blackouts, such as the widespread blackout in the western United States and Canada in 1996. The root causes of these dynamic instabilities are not all well-known and more research is needed. Wide-area real-time monitoring, detection, alarming, analysis and visualization operator tools could be developed to operate the transmission system with smaller dynamic margins. In conjunction with certain control technologies, perhaps energy storage, the tools might be used to mitigate dynamic instability threats, such as to damp oscillations.

New Capacity Transmission Expansion Planning Capability #5: To forecast the need and configuration of new transmission infrastructure far into the future under conditions of growing uncertainty and complexity.

Some enabling new technologies: Although reasonably precise, the traditional deterministic planning tools will increasingly become inadequate for enabling the accuracy needed for expansion planning in a future of growing uncertainty and complexity, which in part will come from the growing use of renewable generation. New planning tools based on probabilistic, multivariate statistical, risk assessment, and other advanced analytical science and mathematical techniques, along with faster computational tools, will be needed.

CHAPTER 4:
Infrastructure Technologies for Renewable Integration

Infrastructure technologies are embodied mostly in hardware devices, equipment and systems deployed in the physical transmission system to increase power flow capacity; control the flow of power; store energy; provide ancillary services, sense and communicate information about physical conditions, improve performance, or protect infrastructure assets and human life. Software often plays an integral role in controlling the behavior the hardware technologies.

4.1 Real-Time Rating Systems

4.1.1 Technology Overview

Real-time rating (RTR) technologies use information, gathered in real time, about the physical condition of the transmission system and its environment to provide capacity ratings that are closer to the actual physical thermal limits than engineering ratings calculated using the traditional or conventional rating methodologies that result in static current (amperage) limits. With this real-time information, transmission system operators can make better-informed decisions about generation dispatch and other operating issues, and system planners can have another tool to deal with transmission capacity expansion planning. RTR technologies have been proposed for situations in which the available transmission capacity, as determined by the conventional utility methods, is a constraint upon the market and business needs of the transmission system users. RTR has mostly been considered for applications where the capacity rating of a transmission line is the constraint, but other system components such as transformers also have thermal ratings that are sometimes the constraining factor in limiting power flow.

Presently, the power flow capacity rating of a transmission line usually derives from the maximum temperature that a line is allowed to reach; sometimes this temperature corresponds to the minimum sag (clearance above ground or objects below the line) permitted by safety codes. There is also a maximum temperature beyond which the wire or cable is physically compromised. The level of current (or power) that corresponds to the limiting temperature or sag is called the static limit. The temperature in a transmission line conductor at any given time is a complex function of internal conductor resistance, current flow, emissivity of the conductor, solar energy hitting the conductor, and convection of heat via the ambient air temperature and wind. Standard and accepted practice is for the utility to assume very conservative bounds on these parameters when setting a line rating, the objective being to ensure the line does not operate in extreme conditions for very many hours. Operation at excessive temperatures can lead to conductor damage, loss of life, violation of clearance requirements due to excessive sag, and line outages. However, the flip side of this approach is that the line is being operated below its actual physical capacity for a large percentage of the time. In cases of transmission congestion or short-term peak overloads, RTR can potentially provide a means to accommodate the needed capacity on a temporary basis, saving transmission users and ratepayers money, and possibly deferring infrastructure upgrades. But without better real-time information, system operators have no alternative but to adhere to the line's static rating to ensure system reliability and integrity.

The objective of RTR, also called dynamic line rating or dynamic thermal rating, is to use real-time thermal-related information about the transmission line and its surroundings to get a better fix on the line's actual capability, and thereby operate closer to the actual line limit. The parameters of the line and conductor are almost always well known, and include the conductor type, mechanical and electrical characteristics, and current condition. The real-time parameters that are needed are current in the line, and weather conditions including ambient temperature, wind speed and direction, and solar insolation. The real-time capacity ratings that are then calculated by the requisite software are made available to the system operators via graphic displays.

Ideally, the capacity rating of every transmission line and transformer in the system would be computed, and made available to system operators and planners, in real time. Operators will have the ratings available via a graphical display; not only will the actual line loading, temperature and real-time capacity be available, but also transient and forecast ratings. Transient ratings would tell the operator how many minutes it will take a line to reach its limiting temperature for a given system contingency (N-1 condition). Forecast ratings would tell the operator what the line capability will be in the future, based on predicted ambient conditions; these ratings would be coordinated with the hour-ahead and day-ahead markets to enable enhanced generator dispatch functions.

RTR systems are combinations of hardware (sensors, data acquisition systems, communications systems) and software, tailored to specific applications related to accessing the latent current (amperage) capacity in transmission systems. These applications include:

Integration of Renewables Technologies – RTR systems have the potential to alleviate constraints on existing lines during times of renewables generation, and in many cases may reduce or defer the need for upgrades of existing lines to accommodate renewables generation. (This does not apply to situations where no transmission exists between the renewables plant and the grid, and some type of transmission line must be built to provide the initial connection.)

Contingency Management – Power transfer is frequently limited because of emergency (30-minute) static ratings of lines that could overload during a contingency (loss of a line). Use of RTR to modify/ameliorate protection schemes, remedial action schemes, etc., could allow higher pre-contingency power transfers, or less severe remedial actions (such as load dropping, generation ramp-down or tripping, etc.) for the same power transfer.

Congestion Management – When access to, or economic dispatch of, generation is constrained due to static transmission line constraints, RTR can allow mitigation of such congestion under favorable circumstances.

Economic Generation Dispatch – Use of RTR on lines that limit the output of generation plants, to increase the plants' availability and efficiency of operation; especially relevant to integration of renewables (wind and solar).

Clearance Management – Use of RTR to monitor or estimate the sag or clearance of transmission line spans, to maintain positive safety margins and ensure reliable operation.

Maintenance Management – Use of RTR to allow system equipment to be taken out of service and maintained during periods when favorable conditions allow other equipment to serve the load.

Static Uprating of Equipment – Analysis of real-time data could enable system planners to re-evaluate the static ratings of equipment by assessing the acceptable levels of risk inherent in static ratings, or re-evaluating the parametric assumptions underlying the ratings. The result would be greater asset utilization of existing lines and corridors and deferred capital investment in new transmission facilities.

4.1.2 New Capabilities Addressed

Access Siting Capability #1: To facilitate environmental and societal deliberations, and enhance acceptability of new transmission lines.

The addition of incremental or intermittent amounts of new renewable generation to the electric system may require increased power-carrying capacity on the transmission lines between the new plants and the load centers. In many cases, this needed capacity, if it is in the range of 10–20 percent of existing capacity, could be addressed with RTR technologies, and would probably not require physical modifications to the existing line conductors and towers. For this reason, the additional capacity could be achieved without the usual difficult process normally required for new lines or line upgrades.

New Capacity Thermal Capability #1: To raise static and physical thermal limits.

The addition of a significant amount of new renewable generation to the electric system will require increased power-carrying capacity on the transmission lines between the new plants and the load centers. In many cases, this will require building new lines where none exist; technologies to be described later will address this issue. For the cases where transmission already exists and the new renewable generation competes for capacity on the lines with other generation sources or represents an intermittent or incremental demand for additional thermal capacity, RTR can be considered as a viable alternative for providing that capacity until new transmission facilities can be built.

4.1.3 Current Status

Many different hardware and software (modeling) systems are available for the purpose of rating of transmission lines. These include:

Thermal Models: The commonly accepted thermal model for a transmission line conductor is embodied in IEEE Standard 738, which defines the parameters and calculations that are gap filling for calculating line ratings on a continuous (static) basis, as well as the commonly accepted default values for those parameters based on industry practice and experience. The values used for the parameters can be default values such as the electrical and mechanical characteristics for transmission line conductors provided by the manufacturers, and (usually conservative) assumptions for wind speed and ambient temperature; but the Standard also provides guidance for the user to use non-default parameters. Uprating a line by re-evaluating the assumptions and parameters previously used to rate it is a straightforward engineering procedure, and has been done in the electric utility industry; doing so usually requires some engineering analysis and/or meteorological studies to provide supporting data and justification for use of the non-default parameters.

Temperature Monitors: Devices that measure the temperature of the conductor directly. If the conductor type is known, the temperature reading provides a means of calculating the line sag, and how much additional current the conductor can carry before its thermal limit is reached. Examples include a commercially available system that measures both conductor surface temperature and line current, infrared monitors, point-contact transducers and distributed fiber optic systems. All of these technologies have issues of cost, installation, maintenance, calibration, accuracy and reliability, and have not been widely used.

Tension Monitors: A device, typically a load cell inserted between the end of the conductor and a dead-end, which measures the tension (mechanical longitudinal strain) on the conductor. This measurement allows the calculation of conductor temperature, sag, and other parameters. This technology has been the most widely used line-monitoring technology to date, with over 300 installations worldwide.

Sag/Clearance Monitors: Devices that measure the distance of a point on the transmission line to the ground underneath it. Examples include video-based systems and systems that use lasers aimed from the ground to the conductor. The video-based system has been field tested and there are several installations in service in the US.

Off-Line Monitoring: Systems that use ambient temperature, wind speed and direction, solar insolation, and other weather parameters from weather stations to calculate a line's rating; no direct measurements of the line are made. Weather information can be used in combination with directly measured line data (i.e., current) to provide calculations of line capacity. EPRI's DYNAMP program is the most widely used for this purpose.

Predictive Rating Methods: Thermal models that have the capability of predicting the end state of a conductor based on simulation of changes in input parameters. For example, if a line is at a steady-state condition, a predictive model could calculate the time it would take a conductor to reach a new temperature based on a step change in current loading. Both EPRI DYNAMP and the commercially available tension-monitoring system have this capability.

Environmental Forecasting Methods: Models and analytical methods for forecasting weather parameters, so that line ratings can be forecast. This is especially valuable for providing forecast ratings to be used in the hour-ahead and day-ahead generation dispatch markets. There are numerous methods and software packages available, but their application to the specifics of transmission line rating has been limited.

Mechanical Sag Limiters: A device with a reverse-temperature characteristic that increases the mechanical tension on the line with increasing temperature, the result being to limit how much the conductor sags under high loading, and effectively increasing the possible power transfer.

This device is still in the development stage; the laboratory prototype has been developed into a field prototype, with testing at utilities planned.

4.1.4 Gaps

Thermal Models: No research gaps. IEEE Standard 738-2006, the most recent revision, provides recommended practices and guidelines for the use of non-default parameters where feasible, for the purpose of dynamic or real-time rating. For example, data from meteorological studies could be used to support the use of wind speeds higher than the assumed 2 ft/sec default value, or ambient temperatures less than the assumed 43º C, enabling higher ratings with minimal increased risk of line overloads. This is already done to produce seasonal ratings (e.g., winter vs. summer), and the approach could be extended to produce ambient-corrected ratings, in which the expected high temperature forecast for a given day is used to set the ratings. IEEE 738-2006 would also be the basis for true dynamic ratings, in which the ratings are constantly changing according to real-time weather and line current measurements.

Temperature Monitors: There is currently just one commercially-available system that can directly measure line temperature and communicate the data to a data acquisition system; it has recently undergone an intensive redesign with updated communications and software, and the manufacturer is beginning targeted utility demonstrations. Infrared monitoring systems, point-contact transducers and distributed fiber optic systems are all still in the RD&D phase. Any temperature sensor installed on a transmission line must be easy to install, self-powered, inexpensive, able to tolerate moisture and contamination, and able to function in and survive long-term exposure to high electric and magnetic fields.

Tension Monitors: Tension monitoring systems are mature and commercially available. Better information about their data accuracy, reliability, and fail-safe mechanisms has been cited by some utilities as a research need to enable more widespread acceptance of the technology.

Sag/Clearance Monitors: The video-based monitoring system is almost fully developed, with ongoing field trials to provide refinements. Information about its ultimate accuracy, reliability, and longevity is a research need. Laser-based systems have been investigated, but need further development to refine them for commercial use and determine their reliability and costs.

Off-Line Monitoring: No research gaps. Further industry experience would foster increased acceptance.

Predictive Rating Methods: No research gaps. Further industry experience would foster increased acceptance.

Environmental Forecasting Methods: Forecasting of ambient temperature is a fairly mature technology and could be easily adapted to forecasting of transmission line ratings. Wind forecasting has traditionally been done for identification of favorable wind generation sites over large areas. This could be beneficial to line ratings if applied over the geographical area of a transmission line, with enough margin of error included to accommodate the variability and intermittency of the wind over the regime studied.

Mechanical Sag Limiters: Evaluation of the second-generation prototype needs to be completed, prior to development of a production-grade model. Further field trials in actual utility use need to be done.

Critical Span Analysis: The so-called critical span is the one span in a transmission line that has the most constrictive thermal constraint, whether due to conductor type, line construction, microclimate, or other reasons. When implementing RTR, it is absolutely essential to monitor or rate the line according to the critical span; to do otherwise would be to risk overloading that span. If on-line monitors are used, their expense and installation requirements dictate that no more of them than necessary be installed, and identification of the critical spans is key to minimizing unnecessary equipment and installation costs. There is no standardized methodology for determining which span or spans are the thermally limiting ones, and depending on changing ambient conditions, the critical spans can be highly variable. One way to deal with this is to put bounds on the ambient parameters so that even under changing conditions an adequate capacity margin can be achieved at minimum risk. But in general, utility engineers that want to use RTR must depend upon industry experience of those companies that have used RTR, or the advice of the companies that supply and install the systems.

Other Gaps: Development of communication systems for multiple-point distributed line sensor networks, and the methods and standards for interfacing them with current utility operating systems and firewalls. Real-time databases and analytical tools for providing processed information to operator screens and to planning engineers. Operator interfaces (GUIs) that display the real-time data in a format acceptable to systems operators.

4.1.5 Gap Filling Research

Research and development in RTR has been ongoing over the last 25 years or so; for this reason, most of the basic tools and methodologies are beyond Stage 3 development status, which means that with some reasonable near-term RD&D effort, RTR can address capacity constraints from renewable technologies by 2020, and possibly by 2010.

Short Term:

Stage 5 efforts:

- Demonstrate an Ambient-Corrected Ratings Methodology.
- Perform a scoping study to identify candidate transmission lines for possible application of RTR technologies, based on the need for uprating; match with potential RTR methods, and perform a screening cost/benefit analysis.
- Perform pilot projects in which RTR technologies are applied to existing lines needing additional capacity to accommodate renewables, including contingency limited situations.

Mid Term:

Stage 4 efforts:

- Develop a Critical Span Methodology.

- Perform a scoping study to develop the requirements and specifications for communications systems and protocols for a wide-area distributed RTR sensing network, and the required operator interfaces, databases and software tools.
- Perform field demonstrations of on-line monitors (temperature, tension, sag) as they become available, to determine their data accuracy and system reliability.

Stage 5 efforts:

- Develop and demonstrate an Environmental Forecasting Methodology, including recommended specifications for weather stations and data needed for the forecasting models.
- Perform pilot projects in which RTR technologies are applied to existing lines needing additional capacity to accommodate renewables, including contingency limited situations.

Long Term:

Stage 3 efforts:

- Research and develop advanced sensor technologies for direct measurement of transmission line temperature, sag and current.
- Research and develop an Intelligent Agent Methodology that integrates multiple distributed transmission line sensors into a real-time thermal management system.

4.2 AC Overhead Line & Conductor Technologies

4.2.1 Overview

The most common way of transporting bulk electric energy is by means of overhead AC transmission lines, which are typically constructed of stranded, bare aluminum or aluminum/steel cables, suspended by insulators from steel lattice towers or wood poles. At some point, the loading limit is reached, and some method must be used to increase the line's capacity. One way, of course, is to build another line, either as a parallel line or higher capacity replacement in the same corridor, or in a suitable alternate route. Assuming that the existing corridor is the only feasible one and has no additional space, there are a number of technological approaches available for increasing the power-carrying capacity within the constraints of the existing ROW.

4.2.2 New Capabilities Addressed

Access Siting Capability #1: To facilitate environmental and societal deliberations, and enhance acceptability of new transmission lines.

The addition of substantial amounts of new renewable generation to the electric system will require that new transmission lines be built between the renewables plants to the existing transmission grid, and also likely require significantly increased power-carrying capacity from the transmission gateways to the loads. These overhead transmission technologies can provide the additional needed capacity with reduced visual and environmental impacts compared to conventional overhead lines, potentially simplifying and easing the permitting process.

New Capacity Thermal Capability #1: To raise static and physical thermal limits.

The addition of a significant amount of new renewable generation to the electric system will require increased power-carrying capacity on the transmission lines between the new plants and the load centers. In many cases, this will require building new lines where none exist; it may also require upgrades to existing transmission gateways and lines. These new overhead transmission technologies can provide technically and economically viable solutions for the needed capability within existing constrained corridors.

4.2.3 Current Status

Reconductoring

Reconductoring involves replacing the stranded conductors in the line with new ones of larger diameter. This is the most common upgrading method, with minimal visual impacts due to the new appearance of the line. Since current-carrying capacity (and by corollary, power transfer capacity) of a conductor is proportional to the cross-sectional area, a conductor of 50 percent larger diameter can have up to 2.25 times the capacity. This increase in conductor size is not difficult to accommodate; if the tower crossarms do not need strengthening, the only modifications needed are replacement of suspension clamps attach the conductor to the insulator string. Even if towers and crossarms need strengthening, the additional costs will still be reasonable, and visual changes to the line will not be significant. The only other issues are possible upgrades to terminal equipment, such as transformers, relays, switches, etc, to handle the additional current; and stability studies to assess the need for greater remedial action for contingencies at the higher current level. In general, this is a mature and cost-effective technology, and is the first and best option for utilities when additional capacity is needed.

Conductor Bundling

Bundling simply means using two or more conductors per phase. Adding a second conductor identical to the first (the usual practice) doubles the current, which doubles the power transfer. Like reconductoring, this is a mature and cost-effective technology that is one of the first alternatives considered by transmission planners, usually involving simple retrofits of suspension clamps, possible replacement of insulators, and possible upgrades to towers and crossarms. Visual impacts are slightly higher than for reconductoring, which may be an issue in the permitting process.

Voltage Uprating

When it is not feasible to increase the current in a transmission line corridor by reconductoring or bundling conductors, the line can be converted to the next voltage level, e.g., from 115 kV to 230 kV. The increase in power is proportional to the increase in voltage, in this case, by a factor of 2. If the existing conductors are used, the only changes to the line itself are new insulators and possibly some strengthening of the towers and crossarms, so the visual impacts are minimal. However, the terminal equipment, including transformers, circuit breakers, relays switches, etc., must be upgraded, and the costs for this will be significant. This is also a mature technology, the cost parameters of which are well known and included in the transmission planning analysis process.

Compact Configurations

This methodology achieves tighter phase spacing within a ROW, allowing more conductors in the corridor. It involves limiting span length, which means more towers per mile, and limiting the sideways movement of conductors, usually by means of insulating spacers. Visual impacts will increase due to the greater number of towers and conductors, as will the costs. Maintenance becomes an issue, requiring new techniques due to the closer spacing of conductors. Compacting lines has the side benefit of reducing the electric and magnetic fields external to the lines.

High Phase Order Lines

High phase order lines have two three-phase lines in a ROW, but the currents and voltages in the lines are 30º out of phase with each other. This is accomplished by using specially designed transformers at the terminals of one of the lines to affect the shift in phase angles. In addition, the arrangement of the phase conductors on the towers is designed to minimize the voltages between the phases, allowing the conductors to be spaced much closer together. The result is more conductors can be fit in the same space, and power transfer through the ROW increased substantially. The main issues are cost of the special transformers, cost of designing complex retrofits to the towers and crossarms, and new maintenance techniques requiring new tools and training procedures.

High-Temperature, Low-Sag (HTLS) Conductors

HTLS conductors use strands of a composite material, rather than steel or aluminum, in the core of a conductor. The composite material is designed to have a higher tensile strength and lower coefficient of thermal expansion, and to take more of the mechanical tension than a conventional conductor. The result is that the conductor can carry more current, claims of more than twice conventional line materials have been made, while sagging less, even though it runs hotter than a conventional conductor. In some cases, the new HTLS conductor is has the same physical dimensions and outward appearance as the conductor it replaces, making retrofit relatively easy, and minimizing visual impacts. There are currently about a half-dozen manufacturers developing HTLS conductors, at least one of which has demonstrated reasonably satisfactory performance of its product in utility field trials. Issues with HTLS conductors include degree of brittleness of the composite core, and the implications for extra care and handling during installation; the cost is considerably higher than for conventional conductors; and longevity is unknown due to lack of experience with these conductors.

4.2.4 Gaps

Reconductoring, Bundling and Voltage Uprating

These are all mature technologies, well-known to the utility industry, cost-effective, and widely used. Barriers to wider use include issues of cost, cost recovery, and visual and environmental impacts that lead to intervention in the permitting process by various stakeholders.

Compact Configurations and High Phase Order Lines

Both of these technologies have had limited use in the US, although the physics and technical barriers are well known; foreign countries have more experience with them, which could be transferred to US utilities. Better information is needed on the design, installation and maintenance requirements of these kinds of lines on American power systems. Potential barriers to wider use include issues of cost, cost recovery, and visual and environmental impacts that lead to intervention in the permitting process by various stakeholders.

High-Temperature, Low-Sag (HTLS) Conductors

A number of utilities are actively looking at HTLS for cost-effective niche applications, such as replacing line segments or spans that are the thermally limiting links in a line, and for tight clearance situations such as road and river crossings where sag must be controlled. More information is needed on installation costs, special installation techniques that may be required, training for line crews and contractors, and longevity in the field. HTLS conductors are still viewed as technically risky and expensive, and only further experience with them will allow these risks to be alleviated.

4.2.5 Gap Filling Research

Mid Term

Stage 4 efforts:

- Field trials of HTLS conductors at utilities to address more applications, gain cost and benefit data, acquire installation and maintenance experience, and help lower costs.
- A scoping study to identify potential applications of compact design and high phase order line configurations, and the technical and cost issues associated with these options, especially in cases of new lines required for renewables and existing lines needing significant capacity upgrades.

Stage 5 efforts:

- Research to clarify cost justification, cost recovery, economic and societal value, and public acceptance of new overhead AC transmission technologies to support regulatory and permitting decisions.

Long Term

- Same as Mid Term (if still needed).

4.3 Underground AC Transmission Technologies

4.3.1 Technology Overview

Conventional underground transmission lines are constructed with copper wires (conductors) encased in an insulating material such as oil-impregnated paper, inside a pipe-type enclosure (conduit), and buried in a trench under special backfill material to dissipate the heat generated in the cables. The inside of the conduit is filled with an insulating oil similar to that used in transformers, or an insulating gas such as SF_6, to provide high dielectric strength (insulating ability between the copper conductors and the conduit, which is at ground potential. Newer types use polyethylene sheathing as the dielectric material, and do not use oil or gas insulating media.

The public generally views underground lines as having far fewer negative impacts than overhead lines, although there are still several difficult issues to address:

- Construction costs for an underground line can be up to 10 times the cost of an overhead line of the same capacity, and construction can take much longer.
- Underground lines are impractical in mountainous areas, where drilling through rock is required.
- The biggest environmental impact will be ground disturbance to in the immediate vicinity of the trench during construction, which can be significantly disruptive, albeit temporary.
- Access to underground lines is more difficult when maintenance is required, which can lengthen outage times.
- Underground lines are more susceptible to damage from construction activities, because they are not visible to crews operating equipment.
- Joints in the conduit can leak, spilling oil into the surrounding soil, or releasing the insulating gas (SF_6 is about 15,000 times more potent as a greenhouse gas than CO_2).
- Lengths are limited to about 40 miles between substations, because of the high capacitive reactance of transmission cables.

4.3.2 New Capabilities Addressed

Access Siting Capability #1: To facilitate environmental and societal deliberations, and enhance acceptability of new transmission lines.

When new transmission lines are needed, the necessary ROW can be difficult to acquire, and interveners and the public may raise a host of objections to overhead lines based on the impacts, including environmental, visual, electromagnetic field (EMF), etc. Experience has shown that the general public is generally more accepting of underground lines because they do not disrupt the visual landscape. The challenge for utilities and other stakeholders is to justify the extra cost if underground lines are proposed as an alternative to overhead lines, and the environment disturbance of trenching might prove objectionable.

4.3.3 Current Status

Conventional pipe-type underground lines using oil or gas insulation are a fairly mature technology, and have been extensively used in the US, particularly in urban areas. Newer types using polyethylene insulation have been used overseas, and are just now coming into wider use in the US, up to 230 kV. The main obstacle to wider use of underground cables is the cost.

4.3.4 Gaps

There have been technological advances in recent years in the construction and performance of solid-dielectric (high-density polyethylene (HDPE) insulated cables. These types of cables have the advantage of using an environmentally-benign technology, in that an insulating oil or gas is not needed. There have been concerns with failure of the polyethylene under conditions of moisture and dirt contamination, which have been correlated with impurities in the polyethylene, and for the most part, addressed by the manufacturers. Installation in trenches is generally easier than for pipe-type cables, although backfill material is still needed in the trench for heat dissipation. The primary technical research need for HDPE cables is better information on revisions to engineering practices and operating standards that are necessary for reliable operation of these cables.

Because of the higher capacitive reactance of underground AC cables vs. overhead lines, the length of underground lines must be limited to about 40 miles before shunt compensation is required. Research into methods of compensating for this capacitance could result in technologies that allow for greater line length.

The main barrier to wider use of underground cables is cost: not just the cost of the cables themselves, but also the costs of constructing the trench for the cable. HDPE technology is helping to make the cable cost itself more reasonable over time, but more economical methods for installing the cable are needed.

The environmental effects of current construction and trenching methods are also significant. To the extent that new technologies such as HDPE are amenable to direct-burial, directional-drilling, or other new and advanced installation methods, both the costs of installation and the environmental impacts of underground cables can be reduced.

4.3.5 Gap Filling Research

Mid Term

Stage 4 efforts:

- Field trials of polyethylene cables at utilities to address more applications, gain cost and benefit data, acquire installation and maintenance experience, and help lower costs.
- Participate in field demonstrations of underground technologies to demonstrate the feasibility and technical issues of applying these technologies in California.

Stage 5 efforts:

- Research to clarify cost justification and cost recovery for new underground AC transmission technologies to support the regulatory and permitting decisions.

4.4 High-Voltage Direct Current (HVDC) Transmission Technologies

4.4.1 Technology Overview

High-Voltage DC (Conventional)

HVDC transmission lines, as they have been typically developed and implemented to date, consist of AC-to-DC converters on the sending end, DC-to-AC converters on the receiving end, and an overhead transmission line or an underground cable system as the transmission path. The converters, which can be considered solid-state transformers, rely on high-voltage, high-power thyristors (semiconductors that are triggered by the AC voltage). Since only two phases are needed for DC, vs. 3 phases for AC, the transmission line, insulators and towers can be more compact and less expensive than AC lines, and less space is needed (and less land needs to be acquired) for the ROW. However, the converter terminals for HVDC are very expensive, being based on high-voltage solid-state electronics and requiring large amounts of AC capacitors at both ends to provide reactive support; thus, intermediate substations for stepping down the voltage add significantly to the cost of HVDC transmission systems. HVDC has traditionally been used when large blocks of power need to be transmitted long distances, and has been used at voltages up to 800 kVDC and several thousand MW of power capability. Historically, the breakeven point for AC-vs.-DC overhead lines has been around 400 miles: HVDC is more economic for transmission distances longer than that (where its lower line costs predominate), and AC is more economic for distances shorter than that (where its lower terminal costs predominate). Underground HVDC cables have an additional advantage over AC cables in that they do not have the problem of AC capacitance; therefore their length is not limited to the 40 miles or so that AC cables are.

HVDC lines have a key strategic advantage over AC, in terms of system control. The power electronics of HVDC provides the ability to specify the power transferred over the line, which AC lines cannot do easily: AC power will flow as Ohm's Law dictates, not necessarily as the system operator desires. Thus, the HVDC power flows can be controlled precisely to ensure that as much of the thermal capability of the transmission system is used as possible. Also, HVDC lines and back-to-back HVDC links can provide a measure of isolation between utility control areas, reducing the impacts of system disturbances and the need to maintain AC synchronism between areas, and enabling control schemes to create "islands" to prevent cascading outages.

AC Line Conversion to HVDC

An existing AC line, whether it is overhead or underground, can be converted to HVDC without modifying the line conductors, towers and insulators in any way; only the terminals need to be modified, with converters installed at the substations in place of AC transformers. Such a conversion can increase the power capability of an existing line by a factor of at least 2 or 3.

Voltage Source Converter (VSC) HVDC Technology

In recent years a new type of HVDC technology has been developed, using voltage-source converters (VSCs) at the terminals of the transmission line. VSCs are less expensive and have more operational flexibility than the conventional current-controlled thyristor HVDC technology, and do not require reactive compensation. Currently demonstrated at voltages up to 300 kVDC, and several hundred MW of power transfer, this type of HVDC technology can also use solid-dielectric cables, the same types that are in common use today in submarine cable and direct-buried (trenched) applications, instead of an overhead line. VSC HVDC can be used to convert an existing AC line to HVDC transmission by using the existing conductors, towers and insulators without modification, and installing VSCs at either end. Alternatively, a VSC HVDC line can be trenched underneath the existing AC line using direct-burial techniques, also adding capacity without modifying the existing overhead AC line in any way, and without adding any additional visual impacts.

4.4.2 New Capabilities Addressed

Access Siting Capability #1: To facilitate environmental and societal deliberations, and enhance acceptability of new transmission lines.

When new transmission lines are needed, the necessary ROW can be difficult to acquire, and interveners and the public may raise a host of objections to overhead lines based on the impacts, including environmental, visual, electromagnetic fields, etc. HVDC overhead lines have the advantage of being more compact than overhead AC lines of similar power capacity, and therefore can fit into more restricted corridors and present a lower visual profile; they also do not have the corona, radio frequency interference (RFI) and EMF drawbacks that AC lines have. If underground HVDC cables are used, visual impacts are avoided, although the environmental issues with constructing the underground trench are similar to AC underground lines; but since HVDC cables do not suffer from the capacitive reactance problem that AC lines have, the length of the line is not limited to the 40 miles or so of AC cables. If the expected power transfer levels are below a few hundred MW, and VSC-based HVDC technology is feasible, the possibility exists to use solid-dielectric, direct-buried cables instead of overhead lines in the ROW. The challenge for utilities and other stakeholders is to justify the extra cost if HVDC lines are proposed as an alternative to AC overhead lines.

New Capacity Thermal Capability #1: To raise static and physical thermal limits.

In the case where more capacity is needed in a corridor that has reached its limit and would otherwise require upgrading, both conversion of an existing AC line to DC and addition of a VSC-based HVDC line in the existing ROW can be feasible approaches to increasing the corridor capacity.

4.4.3 Gaps

The standard HVDC technology as it has been used to date, e.g., in the Pacific HVDC Intertie, the Intermountain Power Project, and many others, is a mature technology that has been continually refined over the last 50+ years, with virtually no research gaps. It is cost-effective for long-distance bulk power transmission when intermediate substations to serve loads along the transmission route are not needed. However, it is likely to be considered too expensive for new line construction for the anticipated power levels of integrating renewables.

Conversion of AC lines to DC lines is fairly straightforward, and most utilities are familiar with the technical and cost issues, as well as when it might be considered a feasible alternative. It has not been done much in the US, for the simple reason that additional ROW and upgraded AC lines have almost always been the feasible alternatives and cheaper than conversion to DC. Now that corridors are getting maxed out, this may be a feasible, albeit more costly, alternative to re-building AC lines or building new ones. Research could focus on identifying the technical issues and risks, refining cost estimates, identifying cases where new lines are needed and HVDC may be an alternative, line upgrades where AC-to-DC conversion may be feasible, and surveying the engineering practices and installation procedures that may be needed.

VSC-based HVDC lines have been installed and successfully demonstrated up to 150 kVDC, at a few hundred MW of capacity; and projects at voltage levels up to 300 kVDC are on the near-term horizon. In the US, there are two East Coast projects where the application was a submarine link between an island and the mainland. VSC HVDC is a very promising technology for linking new renewables plants to the grid where the renewables are remote from the high-voltage grid and nearby transmission does not exist, the capacity needed is a few hundred MW or less, and the distance required is a couple hundred miles or less (which would be uneconomical for conventional HVDC). Research could address the technical risk issues, the potentially feasible sites for integrating renewables in California, and the basic cost/benefit tradeoffs of VSC HVDC where likely applications are identified.

The external barriers to wider use of HVDC technologies are greater than the engineering or technical challenges. Research activities focused purely on technical issues with HVDC technologies are unlikely to make a significant difference in terms of implementing HVDC. The principal stumbling block will continue to be the perceived additional cost per MW of capacity compared to the traditional "least-cost" alternative of overhead AC. What is needed is a comprehensive analysis of the benefits vs. the costs in the regulatory approval process. Inclusion of information about potential HVDC solutions should be included in tools such the Planning for Alternative Corridors for Transmission Lines (PACT) model (discussed in section 6.5), being proposed for use in California, so that all stakeholders and the public have a complete understanding of the possibilities and tradeoffs, and can adequately evaluate all the potential corridor alternatives.

4.4.4 Gap Filling Research

Short Term

Stage 5 efforts:

Research to clarify the technical attributes, cost justification and cost recovery for HVDC transmission technologies, as alternatives for AC lines and upgrades for integrating renewables and for general transmission capacity needs to support the regulatory and permitting decisions.

Mid Term

Stage 4 efforts:

Scoping study to identify candidate transmission projects for connecting new renewables plants, upgrading transmission gateways, and upgrading backbone transmission lines, as information becomes available on where and when new renewables plants will be sited; match with potential HVDC technologies, and perform feasibility and cost/benefit analysis in comparison with traditional AC line alternatives.

Participate in field demonstrations of VSC HVDC to assess feasible applications, refine estimates of construction costs, determine the potential impacts to utility standards and practices, and assess the overall technical risk of implementing the technology.

Stage 5 efforts:

Research to clarify the technical attributes, cost justification and cost recovery for new HVDC transmission technologies to support regulatory and permitting decisions.

Long Term

Stage 4 efforts:

Scoping study to identify candidate transmission projects for connecting new renewables plants, upgrading transmission gateways, and upgrading backbone transmission lines, as information becomes available on where and when new renewables plants will be sited; match with potential HVDC technologies, and perform feasibility and cost/benefit analysis in comparison with traditional AC line alternatives.

Participate in field demonstrations of VSC HVDC to assess feasible applications, refine estimates of construction costs, determine the potential impacts to utility standards and practices, and assess the overall technical risk of implementing the technology.

4.5 Electric Energy Storage Technologies

4.5.1 Technology Overview

Generically, a storage system is any device that stores energy in any form and discharges it in any form. In the AC transmission system, storage systems take AC power from the grid, often convert it to another form, store it, and then return it to the grid as AC power. Storage has number of potentially beneficial applications in the electric system, essentially involving a temporal shift between the generation of electric energy and its consumption. Without storage, the generation and consumption of electric energy must be instantaneous and balanced at all times, a requirement that makes the job of the system operator very important. The operator must forecast loads, manage the generation dispatch markets, and monitor the system in real time to make adjustments on a continual basis, to keep the system balanced and operating correctly. The addition of storage in the proper locations, and of the proper sizes and operating characteristics, would alleviate many of the constraints and issues involved in running the power system. Storage has taken on added importance with the increase of renewables plants, given that the intermittency and variability of renewables increases the complexity of the system operator's job. Until recently using the energy stored in the fuel, including hydro, used in conventional power plants was a more economical means of providing many of the benefits of energy storage per se. However, the increasing costs of many fuels and their environmental consequences, and the decreasing costs of energy storage technologies and improved performance are heightening interest in storage per se.

Storage systems have several basic characteristics that can vary depending upon the technology and the desired application:

- Power capability: how many kW or MW the storage plant can discharge. This is usually a direct function of the electrical generating mechanism, be it a rotating machine or a solid-state electronics interface.
- Bulk energy: how many kWh or MWh of energy can be stored.
- Charge time: the number of hours or minutes required to fully charge the system.
- Discharge time: the number of hours or minutes the system can supply its rated kW or MW output.
- Efficiency: the ratio of energy discharged to the energy required for charging. Also called "round-trip" efficiency. Most storage systems fall into the 60-75 percent range.

- Capital cost: the total cost to build a storage plant; it is usually given in terms of the power capability and bulk energy components.
- Maintenance costs: consist of both $/kW and $/kWh components.

Applications

Applications of storage can benefit the system operator, the utility, and the customer; sometimes it can be of benefit to more than just one party. Because of the generally high costs of storage system, one of the barriers to greater use of storage is that the costs and benefits of a system can accrue to different parties, and it is not clear that the overall benefits may be higher than the costs, particularly if one party, say a utility, would bear the brunt of the costs. Furthermore, current regulatory practices consider storage systems to be generation, making it difficult or impossible for utilities to acquire rate recovery should they choose to install storage.

All of the potential applications of storage are listed here, so that the aggregation of benefits can be evaluated.

Peaking Generation

Storage can "flatten" the load profile of the electric system by charging (using energy) during periods of low demand, and discharging (generating energy) during periods of high demand. This avoids the need for expensive and high-emissions peaking generators such as combustion turbines, and allows for more efficient base-loading of economy sources of generation.

Bulk Electricity Price Arbitrage

Bulk electricity price arbitrage (arbitrage) involves purchase of electricity to charge the storage system when energy prices are low, and selling the energy at a later time when prices are high. This application typically requires a large reservoir for the bulk energy required to be stored and discharged over many hours.

Transmission Thermal Limit Mitigation

Use of storage to provide energy at times of peak loading that would otherwise violate the thermal limits of a line or transformer, with the side benefit of allowing deferral of the need to upgrade those transmission facilities, thereby saving capital dollars. This application could also require a large amount of bulk energy storage capability to ride through the peak loading situation.

Transmission Congestion Management

When a transmission line is thermally or stability limited, congestion can occur: some generators must be paid for their inability to send power over the line, and other generators must be paid extra to generate the needed energy on the other end of the line. Strategically located and sized storage can be used to relieve this congestion and avoid the extra payments to generators.

Transmission System Stability

Use of storage to improve transmission systems' stability by compensating for electrical anomalies and disturbances such as short circuits, voltage sag, switching surges, lightning strikes, load ramps, unstable voltage, and presence of low-frequency oscillations. The result is a more stable system with improved performance and higher transfer capacity. This application implies alternating short-term charge/discharge cycles, so a fast inverter with high kW or MW capability and programmability may be more critical than bulk storage capability.

Time-of-Use Energy Cost Management

This application involves storage used by energy end-users (utility customers) to reduce their overall costs for electricity. Customers charge the storage system during off-peak time periods when electric energy price is low, then discharge the energy during times when on-peak (time-of-use) energy prices apply. It is similar to arbitrage, though the prices paid for energy by the customer are based on the customer's tariff, rather than the prevailing wholesale price for electric energy. Bulk energy capability will be the main consideration.

Demand Charge Management

Energy end-users (utility customers) use energy storage to reduce their overall cost for electric service by reducing on-peak demand charges. To avoid demand charges (associated with a given kW of peak load) customers must avoid using power during peak demand periods, which are the times when demand charges apply. Typically, demand charges apply during the summer months on weekdays. To avoid a monthly demand charge, load must be reduced during all on-peak hours. The kW capability must be selected for the desired amount of demand charge reduction, and the bulk energy storage sized to ride through the peak period.

Electric Service Reliability

The use of storage to provide high quality and highly reliable electric service for one or more adjacent facilities. In case of an intermittent or extended grid outage, the storage system provides enough energy for some combination of the following: an orderly shutdown of customer processes, transfer of customer loads to on-site generation resources, or high-quality power needed for sensitive loads.

Renewables Capacity Firming

Storage is charged with energy from renewables during periods when demand for electricity is low (and thus the value of electricity is low), so that stored energy may be discharged during peak demand periods (when the value is high). This is done primarily to provide power (capacity) in lieu of central generation. Typically this application involves a contract and/or power purchase agreement.

Fast Ramping of Renewables

Some renewables plants have the characteristic of fast ramp-up and ramp-down, due to the sudden presence or absence of the wind or the sun. These ramps can be forecast to some degree, but some non-renewable generation sources that are under the control of the system operator are needed to compensate for this fast ramping. Storage would be a cleaner alternative than fossil-fired sources to accomplish this function.

Renewables Contractual Time-of-Production Payments

This application involves storing of electric energy from renewables during periods when demand for electricity is low (and thus value of electricity from renewables is low). The energy is discharged during peak demand periods when the value is high. For the entity purchasing the energy this is done primarily to provide the energy in lieu of producing the same energy from a non-renewable central generation facility. Typically, this application involves a contract and/or power purchase agreement.

Ancillary Services

These are functions that are provided by generators on the electric system, aside from the main function of supplying bulk electric power, at the direction of the system operator. They include spinning reserve, generation reserve, load following, energy regulation, frequency regulation, and black start. Some of these services depend more on the kW size, and others on the kWh parameter.

Types of Storage Technologies

Hydro plants: store the potential energy in water, and discharge it as electricity. A pumped hydro plant has an upper and a lower reservoir; it uses electric energy from the grid to pump water from the lower reservoir to the upper reservoir during times of low system load, then run the water back through a hydro turbine to generate electric energy when power is needed, typically during peak load periods. Response time to system demands can be on the order of minutes.

Batteries: AC power from the grid is converted to DC power and then into chemical energy in the electrolyte of batteries, and discharged back into the grid as AC when needed. Battery media include lead-acid (both liquid and gel type), nickel-cadmium, nickel metal-hydride, and lithium-ion. Requires a power electronics interface to convert AC to DC and back again, but the advantage of the electronics is faster response of the storage system to grid demands, on the order of milliseconds.

Flow Batteries: Basically a reversible fuel cell with an external electrolyte tank. Fuel cells use hydrogen as fuel in a chemical reaction to produce electricity, heat and water vapor. Flow batteries can reverse the process, using electricity from the grid during the charging cycle to produce the hydrogen and oxygen needed for the generation (discharge) cycle. Electrically, it acts just like a large battery storage system. Major types include vanadium-redox and zinc-bromine.

Flywheels: AC power from the grid is converted to DC power and then into rotating energy in the flywheel, and discharged back as AC when needed. The system uses a power electronics converter/inverter to interface with the AC grid.

Compressed air energy storage (CAES): AC power from the grid is used to run motors to compress air; the air is used to run turbines to produce AC power when needed. Similar to hydro plants in terms of response time.

Supercapacitors: Capacitors using advanced materials and designs for higher energy storage density and performance; potentially higher reliability and life due to simplicity of construction. Efficiencies are projected to be better than 80 percent. Also use power electronics interfaces, and can respond very quickly to system demands.

Superconducting magnetic energy storage (SMES): Magnetic coils using superconducting materials to store electric energy in the form of electric current, the only form of storage to do so. With zero impedance (no resistance or reactance) in the superconducting state, SMES is potentially one of the most efficient storage media, potentially in the 90-95 percent range. Very fast response, as it also uses a power electronics interface.

Plug-in hybrid electric vehicles (PHEV): Future PHEVs are anticipated to have expanded battery power for extended electric-only operation, and presumably they will largely recharge overnight, when system loads are usually at low levels. Potentially, PHEVs could be used by the electric system as a source of storage, the objective being to utilize available economy generation or the generation from plants that are desired by system operators to remain on the system during low-load periods, then dispatch the PHEVs when peak loads occur. In particular, wind generation, which in California tends to be abundant at night, has a high potential for synergistic operation with PHEVs.

Intelligent Agents: An Intelligent Agent is a software-based system capable of monitoring and controlling the operation of distribution and/or transmission level assets in response to external market signals, or in the context of system control strategies, whether hierarchical or local. These assets can consist of a mix of central-station and distributed generation (including renewables) and storage assets (flywheels, batteries, capacitor banks, etc.), each with a differing response characteristic, and responding to control/market signals to maximize the value of the renewables assets.

4.5.2 New Capabilities Addressed

New Accommodation Ramping Capability #1: To reliably respond to rapid up and down power ramping.

See application Fast Ramping of Renewables, above. Storage systems can alleviate the need for additional non-renewable generation operated in conjunction with renewables.

New Accommodation Power Market Capability #2: To enable intermittent renewables to participate in power markets on equal basis.

The applications Renewables Capacity Firming, Renewables Contractual Time-of-Production Payments, Ancillary Services, Transmission Congestion Management, Peaking Generation and Transmission System Stability all enable renewables to participate in the generation and ancillary services markets on a more equitable footing.

New Accommodation Dynamic Behavior Capability #3: To operate the grid in response to renewable power plant dynamic behaviors.

See Transmission System Stability, above. Storage systems can be cost-effectively used as controls to damp system oscillations and help maintain system stability.

New Capacity Voltage Stability Capability #2: To relax, or eliminate need for, voltage stability constraints.

See Transmission System Stability, above. Storage systems can provide voltage support and voltage regulation services to maintain voltage stability.

New Capacity Transient Stability Capability #3: To relax, or eliminate the need for, transient stability limits.

See Transmission System Stability, above. Storage systems can provide voltage support that is a key factor in transient stability, and can also be used as damping controls to suppress system oscillations.

New Capacity Dynamic Stability Capability #4: To relax, or eliminate the need for, dynamic stability limits.

See Transmission System Stability, above. Storage systems can provide voltage support that is a key factor in dynamic stability, and can also be used as damping controls to suppress system oscillations.

New Capacity Thermal Capability #1: To raise static and physical thermal limits.

See Transmission Thermal Limit Mitigation, Transmission Congestion Management, above.

4.5.3 Gaps

Pumped Hydro: The technology itself is mature, with few research gaps. It can be relatively inexpensive to build and operate, as it uses conventional AC power generation technology. Pumped hydro is very site-dependent, and most of the best sites are already developed; therefore, it can't always be located where it's needed in the transmission system. Some recent work has been done on the feasibility of using underground caverns for the reservoirs.

Batteries: The energy density of chemically-based battery systems is not as high as desired, requiring a fairly large footprint for even modestly sized battery systems for utility applications. Costs in both per-kW and per-kWh terms are relatively high. There are significant maintenance requirements including periodic replacement of internal components, safety issues with the chemicals involved, and life expectancy.

Flow Batteries: Still in the RD&D stage, also very expensive, with significant maintenance and safety issues, and unknown longevity due to limited industry experience.

Flywheels: Still in the developmental and RD&D stages; relatively small unit size (about 25 kW per flywheel) means many units must be aggregated for utility-scale applications; installed costs are high although they should come down with volume production; maintenance costs are projected to be low because of the magnetic bearings used in the rotor; reliability is expected to be high due to relatively simple design and few moving parts.

Compressed air energy storage (CAES): A fairly mature technology, very site-dependent, as a suitable repository for the air is needed, such as a salt cavern. Typically requires a natural gas-fired turbine in conjunction with the electrical generator, due to the extreme cooling of the air upon expansion in the generation mode. Further research could be done to find a way to avoid the need for a combustion turbine.

Supercapacitors: Very expensive for grid applications, in terms of $/kWh of storage, and the need for a power electronics interface, but could become cost-effective and feasible over time as costs come down.

Superconducting magnetic energy storage (SMES): SMES has been successfully demonstrated for small-scale distribution system applications, such as power quality and reliability. The biggest issue with SMES is cost: even with advances in 2nd-generation superconducting materials technology that can operate at higher temperatures, thereby reducing materials and cryogenic system costs, the cost of building a superconducting coil has increased significantly, especially for utility-scale applications.

Plug-in hybrid electric vehicles (PHEV): PHEVs are not yet widespread, and so may not make an impact on the grid for a number of years. If they do become abundant, and are tapped as storage by the grid, coordinating PHEV electric demand with wind generation in a "smart" infrastructure can mitigate renewables' impacts to the grid, as well as helping to firm the output of renewables for participation in the generation and ancillary services markets. A number of issues would need to be studied for this to work, such as: data requirements and availability; the potential value of the service on a per-vehicle basis; infrastructure and communications requirements; potential integration with Smart Grid and Demand Response systems; estimation of the relative rates of growth of penetrations of wind generation and PHEV load; and potential costs and benefits of vehicle-to-grid supply should battery systems be developed that can accommodate it.

Intelligent Agents: The Energy Commission is currently conducting a project in concert with the California Independent System Operator (Cal ISO) to apply Intelligent Agent technology to the coordination of energy production and delivery from wind generation resources. The agent-based control system will incorporate flywheel storage technology to further improve the dynamic control of the wind generation resources. This multi-phase project will allow for the project team to first characterize the problem and the associated agent-based solution, then demonstrate the agent-based control at Southern California Edison (SCE) transmission facilities in the Tehachapi area. A successful project will demonstrate that applying agent technology in this way expands the potential delivery of renewable energy and use of existing transmission facilities for the benefit of the consumers in California, and extension of the methodology to include more types of storage and wider areas of the transmission grid will require additional research.

4.5.4 Gap Filling Research

Short Term

Stage 4 efforts:

- Participate in feasibility demonstrations and field trials of storage technologies in applications for integrating renewables and providing grid support functions.

Stage 5 efforts:

- Research to clarify the technical attributes, benefits, cost justification and cost recovery for storage technologies that are cost-effective for niche applications, when proposed for use in integrating renewables and for general transmission capacity and operational needs.

Medium Term

Stage 3 efforts:

- Capitalize upon the success of the project Agents for the Integration of Storage and Renewables ("Intelligent Agents"), currently nearing completion by the Energy Commission, by extending the methodology to include more types of storage and wider areas of the California transmission grid, and demonstrating improved capabilities for managing grid assets to maximize the benefits of renewables assets.

Stage 4 efforts:

- Perform scoping studies to identify and characterize candidate storage project applications in conjunction with new renewables plants, planned transmission upgrades, and system operational needs, as information becomes available on where and when new renewables plants will be sited, and the attendant transmission facilities and operational needs become apparent; match applications with potential storage technologies, and perform feasibility and cost/benefit analyses for the identified storage applications.
- Participate in field demonstrations of storage technologies to assess feasible transmission system applications, refine estimates of construction and O&M costs, determine the potential impacts to utility standards and practices, and assess the overall technical risk of implementing the technology.

Stage 5 efforts:

- Research to clarify the technical attributes, benefits, cost justification and cost recovery for storage technologies that are cost-effective for utility applications, when proposed for use in integrating renewables and for general transmission capacity and operational needs.

Long Term

Stage 3 efforts:

- Perform research to evaluate the impacts of PHEVs on the transmission system, study the potential benefits of PHEVs to the grid, assess the potential of using wind generation for charging of PHEVs, and identify the technical and infrastructure requirements for managing wind and PHEVs within an advanced energy management system, such as an Intelligent Agent system.

Stage 4 efforts:

- Perform scoping studies to identify and characterize candidate storage project applications in conjunction with new renewables plants, planned transmission upgrades, and system operational needs, as information becomes available on where and when new renewables plants will be sited, and the attendant transmission facilities and operational needs become apparent; match applications with potential storage technologies, and perform feasibility and cost/benefit analyses for the identified storage applications.
- Participate in field demonstrations of storage technologies to assess feasible transmission system applications, refine estimates of construction and operating and maintenance

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4.6 Power Flow Control Technologies

4.6.1 Technology Overview

The AC electric power system, by its nature, does not have a high degree of controllability, in terms of system operators being able to designate which transmission paths the power flows on. The electric system is a giant interconnected network of generating sources, loads (customers) and the transmission and distribution lines that provide the connections among them all. To a great extent, the power flows on the system are determined by the customer loads and the generators that are on the system at any given time; the power then flows over the transmission and distribution lines as determined by the impedance of the lines and paths and Kirchhoff's laws. Because of the numerous parallel paths that power can flow on, the contract path for power, defined as the line or path over which the contracted power from a generator to a load is meant to flow, is not necessarily the only path over which that power will flow. For example, Bonneville Power Administration (BPA) can contract with Pacific Gas and Electric (PG&E) to send 3,000 MW of power over the 500 kV Pacific Intertie, but in reality about 20 percent of that power can flow through parallel paths on the eastern side of the Western Electricity Coordinating Council (WECC) system. This phenomenon, called loop flow or inadvertent flow, frustrates the efficient exchange of power within transmission grids and between utilities, and can result in diseconomies.

For controlling real power, system operators have just a few tools at their disposal. They can adjust the output of generators under their direct control; however, in today's power markets, this control is diminishing. When lines or paths reach their thermal or stability limits, congestion occurs, and generators are forced to adjust their outputs to relieve the line overloads, with congestion payments both to generators who must curtail and to reliability-must-run generators who must generate in their place. Series capacitors in the transmission lines can be switched in or out to reduce or increase, respectively, the impedance of a line or path, increasing or decreasing the power flowing in that path; this is typically not a real-time control option, as most series capacitors are manually switched, usually on a seasonal basis. Devices called phase-shifting transformers are sometimes used to increase the apparent impedance of a line or path, the objective being to shift power flow from a specific line or transmission path to adjacent circuits or paths. The only other options for controlling real power are to change the configuration of the lines in the system, i.e., switch lines in or out, or to change the bus connection arrangements in the substations; neither of these are generally desirable options, and cannot be done feasibly on a real-time basis.

HVDC transmission lines (see section 4.4 on HVDC Transmission Technologies), in contrast to AC lines, have the ability to control their power flow due to the power electronics in the converter stations at the terminals of the lines. There are currently only a few HVDC lines in the Western grid, whose purpose in mainly to transmit large blocks of inexpensive but remote generation to load centers in Southern California. Asynchronous HVDC links, also called back-to-back HVDC links, are sometimes used to provide control and isolation between utility control areas: the power transfer between the areas can be precisely controlled, and the system frequencies of the adjoining systems do not have to be in synchronism with each other, and system disturbances do not propagate through the links as they would through AC lines.

Reactive power is much more controllable than real power. Generating plants have the capability to adjust their volt-amps reactive (VAR) outputs automatically to match the reactive demands of the system. Shunt capacitors and inductors can be installed at any substation, and are switched in and out as needed (not always in real time) to control the voltage profile of the system and adjust to the reactive power demands of the loads on a local as well as system level. Series capacitors also help to control voltage levels by reducing the reactive impedance of transmission lines. Devices called synchronous condensers can provide a measure of dynamic voltage control. Synchronous condensers are rotating synchronous generators without prime movers, and appear as reactive power devices only; by adjusting their excitation systems (voltage to the stator coil) they can either produce or consume VARs. Transmission transformers, for the most part, do not have tap changers and can't control voltage. Distribution transformers (transmission voltage to distribution voltage) can have some measure of voltage control to adjust to the demands of the loads on the distribution side.

Other control methods are used in the context of remedial action schemes to control system stability: generator dropping, load dropping, fast reactor insertion, series capacitor switching, and braking resistors, to name the major ones.

A new generation of control devices based on high-power electronics technology, utilizing gate turn-off (GTO) thyristors, has been developed over the last 30 years or so. Developed predominantly by the Electric Power Research Institute (EPRI) and called Flexible AC Transmission Systems (FACTS), include:

- Static VAR Compensator (SVC): Thyristor-controlled switching of capacitor and inductor banks to provide real-time control of voltage, using existing AC capacitors and inductors.
- Static Synchronous Compensator (STATCOM): A fully solid-state device that can produce either inductive or capacitive VARs for real-time control of voltage. It performs the same function as a synchronous condenser.
- Thyristor-Controlled Series Capacitors (TCSC): Series capacitors with thyristor switching to provide real-time control of line impedance.
- Static Series Synchronous Condenser (SSSC): A fully solid-state version of the TCSC.
- Unified Power Flow Controller (UPFC): Basically a combination of the STATCOM and SSSC, placed in series with a transmission line to control its power flow.
- Thyristor-Controlled Phase Shifter (TCPS): A thyristor-controlled phase-shifting transformer, to provide real-time control of phase angle.
- Interline Power Flow Controller (IPFC): Controls the power flows on two adjacent lines to maximize transfer capacity of the two circuits.
- Convertible Static Compensator (CSC): A device that, depending upon the configuration and control strategy desired, can operate as a STATCOM, SSSC, UPFC or IPFC.

FACTS devices are a relatively mature technology, and are commercially available. They tend to be very expensive due to the high cost of fabricating the high-power thyristors, hence have seen somewhat limited application in US power systems. EPRI and others have been researching a new thyristor technology, called Super-GTO thyristors that are an order of magnitude smaller and more efficient than conventional thyristors, and have the potential to make FACTS devices much more cost-effective.

Fault Current Controllers (FCCs) are an emerging technology that are designed to control system currents under fault (short-circuit) conditions. As loading on the system grows and new transmission lines and upgrades have not kept pace, the magnitude of fault currents experienced by transmission lines is also growing, and in many cases threatens to exceed the ability of circuit breakers to safely and reliably interrupt the faults. Aside from undesirable solutions such as installing substation neutral reactors, splitting substation buses, or derating circuit paths, what is needed is a new class of devices to control the fault currents by keeping them within the capabilities of the available circuit breakers. Fault current controllers are currently in the RD&D phase, with several manufacturers testing prototypes in the 15 kV class, with plans for eventual development to at least 138 kV within about 5 years. Prototypes include an EPRI power electronics-based unit, a device developed by the Department of Energy (DOE) with a private vendor, and devices using superconducting technologies from two private manufacturers.

A distributed line-impedance control device is currently being developed by Georgia Tech's NEETRAC Laboratory, the purpose of which is to control power flow in a transmission line. The device is mounted on the transmission line conductor, derives its power from the current in the line, uses that power to synthesize reactive power via power electronics, and injects it into the line. A number of these devices are installed at various points along the transmission line, according to how much total line compensation is desired. If inductive power is injected, the effective impedance of the line is increased, and power flow is reduced or limited; if capacitive reactance is injected, the effective impedance of the line is reduced, and power flow is increased in the line. This device is currently in the RD&D phase, with a field trial at a utility planned within the next year. Current models have fixed set points of line current at which they start to operate, which is designed for limiting the current to the line's rating; future models are projected to have communications capability so that the set points can be set remotely for a dynamic rating capability.

Models for advanced controls must be included in the analytical programs currently used by planning and operating engineers to evaluate system performance. For the most part, individual models have been developed for the control devices mentioned here, and much research has been done in terms of how these models are integrated into the larger computer models for system planning, and also for hierarchical control strategies to coordinate the operation of these devices. Research to validate these models, further refine them, and integrate them into planning studies and control strategies in the operational arena is needed.

4.6.2 New Capabilities Addressed

New Accommodation Dynamic Behavior Capability #3: To operate the grid in response to renewable power plant dynamic behaviors.

Advanced controls can contribute to accommodating the effects of renewables plant dynamic behaviors, when used as control elements in an integrated, intelligent control methodology.

New Capacity Voltage Stability Capability #2: To relax, or eliminate need for, voltage stability constraints.

Advanced controls and FACTS devices such as the SVC, STATCOM, TCSC, and SSSC can provide dynamic voltage support to address voltage stability limits, when used as control elements in an integrated, intelligent control methodology.

New Capacity Transient Stability Capability #3: To relax, or eliminate the need for, transient stability limits.

Fault current controllers can directly address the transient stability issue by controlling and limiting fault currents, preserving the stability margins of the system. FACTS devices can provide active damping of oscillations when used as control elements in an integrated, intelligent control methodology.

New Capacity Dynamic Stability Capability #4: To relax, or eliminate the need for, dynamic stability limits.

Advanced control devices can provide active damping of dynamic instability and low-frequency oscillations when used as control elements in an integrated, intelligent control methodology.

New Capacity Thermal Capability #1: To raise static and physical thermal limits.

Advanced controls that divert power from lines with thermal limits to lines with available capacity can effectively relax thermal constraints and enable better utilization of existing system capabilities, avoiding the need for new lines or upgrades.

4.6.3 Gaps

For Fault Current Controllers, more research needs to be done, and is ongoing, to demonstrate the feasibility and performance of these devices and then develop them for higher voltage levels. The prospects for development and availability of new circuit breakers with higher fault current interrupting capability are not very positive in the near to midterm, increasing the urgency for fault current controller technology.

Most of the FACTS-type devices are relatively mature in terms of design, performance, reliability and longevity. The main issues are cost, which inhibits wider use of the technology; and to some extent technical risk, in that most utilities have little or no experience with HVDC or advanced control technologies. Emerging Super-GTO thyristor technology holds promise for reducing the cost, and also the size, of solid-state controls, and improving their efficiency as well.

A distributed line-impedance device shows promise as a more cost-effective way of controlling power flow than FACTS devices to date. Further proof of concept testing and refinement of the device for mass production are needed, as well as cost/benefit analysis when commercial products are available.

In the modeling arena, more work needs to be done in refining and verifying the analytical models of these devices for inclusion in planning and operating simulation studies.

Control strategies, such as Intelligent Agents, need to be developed and demonstrated to allow automatic hierarchical control of the system.

Wide-area sensors (PMUs) and communications systems need to be further developed to provide the observability of the system and the data for the necessary control algorithms.

4.6.4 Gap Filling Research

Short Term

Stage 3 efforts:

- Participate in research and development of Fault Current Controller prototypes.

- Perform a scoping study to identify feasible applications of advanced controls, especially where integration of renewables plants is anticipated.
- Develop advanced models for control devices and perform verification studies of those models in planning and operation simulation programs.

Stage 4 efforts:

- Participate in feasibility demonstrations and field trials of control technologies in applications for integrating renewables and providing grid support functions.
- Develop advanced control methodologies such as Intelligent Agents and real-time optimization programs.

Medium Term

Stage 4 efforts:

- Participate in feasibility demonstrations and field trials of control technologies in applications for integrating renewables and providing grid support functions.
- Develop advanced control methodologies such as Intelligent Agents and real-time optimization programs.
- Participate in field trials of the advanced prototype of the distributed line impedance device.

Stage 5 efforts:

- Participate in field trials of high-voltage FCC devices.

Long Term:

Stage 4 efforts:

- Develop advanced control methodologies such as Intelligent Agents and real-time optimization programs.
- Participate in feasibility demonstrations and field trials of control technologies in applications for integrating renewables and providing grid support functions.

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4.7 Superconducting Technologies

4.7.1 Technology Overview

All materials used in power system equipment have some degree of resistance to the flow of electrical current. This resistance causes internal losses in the form of heat, and imposes limits on the amount of current that a piece of equipment can handle without damage. The evolution of power system equipment has been an ongoing process of refinement, with a constant search for greater efficiency and reduced losses in transporting electric energy, with the result that power equipment using the technologies known today is virtually at its zenith, as far as equipment efficiency is concerned. Clearly, only a technology breakthrough can change this picture in the future. Superconductivity just might be that breakthrough.

4.7.2 New Capabilities Addressed

Access Siting Capability #1: To facilitate environmental and societal deliberations, and enhance acceptability of new transmission lines.

HTSC cables will be able to handle the same amount of power as conventional overhead or underground transmission lines, in a much smaller ROW. The cables could easily be placed underground, reducing visual impacts, and helping to facilitate new transmission connections to remote renewables plants.

New Accommodation Dynamic Behavior Capability #3: To operate the grid in response to renewable power plant dynamic behaviors.

New Capacity Voltage Stability Capability #2: To relax, or eliminate need for, voltage stability constraints.

New Capacity Transient Stability Capability #3: To relax, or eliminate the need for, transient stability limits.

New Capacity Dynamic Stability Capability #4: To relax, or eliminate the need for, dynamic stability limits.

Superconducting control devices may have numerous applications in voltage support, stability and other grid services in coordination with intermittent renewables plants.

New Capacity Thermal Capability #1: To raise static and physical thermal limits.

HTSC cables would address the need for increased corridor capacity by providing much higher power transfer capability in the same ROW as an existing, conventional transmission line.

4.7.3 Current Status

Superconductors are a class of materials that are characterized by zero resistance to the flow of electricity when they are cooled to a sufficiently low temperature. First-generation (1G) superconducting materials required liquid helium to be cooled sufficiently (about 3º above absolute zero, or 3 K) to become superconducting. Second-generation (2G) materials being developed today become superconducting at the temperature of liquid nitrogen (77 K), a significant improvement; they are called "high-temperature superconductors (HTSC)," because 77 K is high compared to 3 K. Whereas 1G materials were brittle, hard to fabricate into wires, and difficult to install as windings in power equipment without breaking, 2G materials are more robust and easier to work with, as well as cheaper. Also, the cost and complexity of the cryogenic system for 2G superconductors is much less than it was for 1G superconductors, given the relative availability of nitrogen vs. helium.

The use of superconductors in power equipment means that at least an order of magnitude increase in current-carrying capability is possible in the same space occupied by conventional materials. (A superconductor's upper current limit is its critical current, above which it loses its superconducting behavior.)

Research efforts have enabled great strides in developing superconducting versions of power system devices. Those undergoing development or field demonstration today include:

- Cable systems: Manufacturers of wires and conductors for underground cables have teamed with superconductor firms, cryogenics manufacturers and the US DOE to build and test superconducting cables of lengths up to about 1,000 feet. The conduit encasing the superconductors holds the liquid nitrogen.
- Fault current controllers (FCCs): Two manufacturers have developed 15 kV class FCC prototypes, using different technical approaches, but both utilizing the properties of superconductors to limit fault currents.
- Superconducting magnetic energy storage (SMES): A coil of superconducting wire that can store AC electric energy as DC electric energy and discharge it back to the grid as AC energy, via a power electronics interface. Small units are currently in use on the

distribution system as power quality devices, allowing ride-through of short-duration power outages to protect sensitive loads.

- Superconducting transformers: One manufacturer has just produced a 1 MVA superconducting transformer of significantly smaller size and lighter weight than a conventional transformer of the same capacity, with plans to develop it to 30 MVA in the near future.
- Superconducting motors. Major applications that have been identified include ship and train propulsion, and large (1,000+ horsepower) industrial motors.
- Superconducting generators. Several first-generation prototypes on the 50-100 MVA range were successfully demonstrated with efficiencies approaching 98 percent.
- Superconducting synchronous condenser. Synchronous condensers are rotating synchronous generators without prime movers, and appear as reactive power devices only; by adjusting their excitation systems (voltage to the stator coil) they can either produce or consume VARs. A commercially available superconducting synchronous condenser has about 4 times the reactive capacity as the same-size conventional unit it replaces.

4.7.4 Gaps

HTSC cable systems are approaching commercial viability. Current demonstration projects are focusing on the performance of the HTSC materials themselves, and pushing the envelope of segment length, which is limited by manufacturing processes to about 1,000 ft. Splicing techniques that are required to form longer lines are also being developed and tested. It is recognized that cryogenics systems used today need to be improved, made more efficient, and requiring less maintenance; the answer may be pulse-type compressors, as used in small-scale applications at present.

Fault current controllers are still in the beta testing and proof of concept phases, and voltage levels have yet to be pushed to those suitable for transmission applications.

4.7.5 Gap Filling Research

Short Term

Stage 3 efforts:

- Monitor the field of superconducting technologies for promising developments and products that could address California's transmission system needs.

Stage 4 efforts:

- Participate in research and development and targeted field experiments of superconducting Fault Current Controller prototypes.

Medium Term

Stage 5 efforts:

- Participate in advanced prototype demonstrations and field trials of superconducting technologies, with emphasis on leveraged projects with utilities, manufacturers and the US DOE.

Long Term

Stage 5/6 efforts:

- Participate in advanced prototype demonstrations and field trials of superconducting technologies, with emphasis on leveraged projects with utilities, manufacturers and the US DOE.

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CHAPTER 5: Real-Time Systems Operations for Renewable Integration

5.1 Technology Overview

While technologies can be used to bring new or enhanced capabilities to the transmission infrastructure for meeting the three major objectives via new hardware measures, technologies can also bring new capabilities for operating the infrastructure in a reliable, economic and integrated fashion. Indeed, given the additional operating uncertainties that renewable generation will likely add, the new operating capabilities will be a necessity, especially those for real time and wide-area systems operations. This class of technology generally consists of sensors for detection and measuring of system conditions; communication systems; data management; analysis for monitoring, diagnosis, prediction and decision support; visualization for human interface; and instructions for automation. Much of this technology platform is enabled by an emerging sensing technology known as synchrophasors or, more commonly, phasors.

While phasors and other types of sensors enable virtually all real time system operation, the hardware technology is relatively mature and the emerging technology is characterized by the applications or software tools by which these sensor systems are applied.

5.1.1 Synchophasor Technology

Synchrophasors measure voltages and currents (usually expressed as the magnitude and phase angle of a sine wave), at diverse locations on a power grid, and can output accurately time-stamped voltage and current phasors based on a common time source, usually a GPS clock. In accordance with generally accepted practice, this report will use the term “phasors” rather than “synchrophasors” to refer to this high resolution, time-synchronized measurement technology. Because these phasors are truly synchronized, comparison of two voltage and current quantities is possible, in time. These comparisons can be used to assess overall power system conditions. Some have likened the advancement that phasor measurements bring over traditional SCADA information to the advancement that MRI has brought to medical diagnosis over x-rays.

A phasor data collection system contains an array of phasor measurement units (PMUs) at key locations throughout the area of interest. PMUs are an established monitoring technology that, when widely deployed throughout the power system, provides grid operators with unprecedented real-time information of grid status, and detection and diagnosis of events over a wide-area. Collecting satellite time-stamped data at speeds up to 60 times a second, PMUs, placed optimally in the transmission grid, can provide the operator an “over the horizon” real-time, early-warning view of grid conditions that might represent a threat to the reliable, economical and secure operation of the California transmission system, and take mitigation actions. In the Cal ISO region, over 50 PMUs are currently linked.

The evolutionary roles of this important PMU monitoring, communications, data storage and data analysis component of the smart power grid technology platform [9] are to provide real-time wide-area situation awareness, state forecasting, operator decision support, model benchmarking, post-disturbance analysis, intelligent grid protection, and automated response and control. It is essential to many of the capabilities for increasing transmission path capacity and accommodating renewable plant characteristic behaviors.

Because of the potential for this next-generation of paradigm-shift, smart grid technology to enable significant improvements in operating, maintaining and planning of the electrical grid that would not be otherwise possible and, furthermore, to ultimately change the economics of power delivery, the Energy Commission funded the Phasor Measurement Application study conducted by KEMA [10]. This study analyzed major PMU applications and their public-interest reliability and business benefits, status of development and deployment, and identified implementation gaps. The phasor applications benefits analysis resulted in recommendations for near-, mid-, and long-term research, development, and deployment roadmap and a process to transition PMU technology to full commercial application. This report also provides an excellent source of the information about the current status of phasor measurement technology and system architecture issues associated with phasor data collection, communication, data storage, archiving and retrieval engineering issues.

5.1.2 Demand Response

Demand response is generally meant to refer to the ability to selectively decrease (or increase) load in a manner which does not noticeably inconvenience the customer. Cal ISO has defined several types of demand response programs[11]:

- Price Sensitive load that is willing to reduce demand for the right price. Demand that is bid into Day-Ahead markets to reduce peak load and load that will curtail in real-time for the right price.
- Interruptible Load – Loads that are willing to be interrupted or curtailed under emergency conditions and will immediately take action in response to a dispatch notice.
- Frequency sensitive load – Load that is willing to turn off or reduce consumption due to a drop is system frequency. One example is a Plug-In Hybrid Vehicle program that will automatically stop charging their batteries when the frequency is low.

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9 DOE Office of Electricity Delivery & Energy Reliability; Grid 2030 vision; http://www.oe.energy.gov/smartgrid.htm

10 Novosel, Damir, Bill Snyder, Khoi Vu, (KEMA Inc.) and Jim Cole (University of California, - California Institute for Energy nd Environment). *A Business Case Study on Applying Synchrophasor Measurement Technology and Applications in the California and the Western Electric Coordinationg Council Grid*. California Energy Commission, CEC-500-2013-045 http://www.energy.ca.gov/2013publications/CEC-500-2013-045/CEC-500-2013-045.pdf

11 *CAISO Plan for Integration of Renewable Resources Hawkins Presentation*, EPRI Webcast, May 28, 2008,

- Load that is willing to change based on availability of excess wind generation production

Demand response is expected to play an important role in the integration of renewable resources into the grid. It is, however, a subject considered beyond the scope of this report and will not be discussed further.

5.2 Disturbance Detection, Diagnosis and Compliance Monitoring

5.2.1 New Capabilities Addressed

In addition to enhancing grid reliability and avoiding major blackout conditions, the KEMA study identified Disturbance Detection, Diagnosis and Compliance Monitoring as a phasor application that offers the potential to significantly reduce the capacity derating of key transmission pathways that are critically important for 33 percent and greater renewables integration. This would seek to analyze PMU data from various locations within the regional power grid to detect, diagnose and mitigate low frequency oscillations and, through improved operating tools, free up significant underutilized transmission capacity for importing renewable power into the state and into major urban areas.

5.2.2 Current Status

The use of PMU data for post disturbance analysis is increasingly being acceptable by grid operators and engineers as a cost-effective method for understanding the causes of major grid blackouts and disturbances and identifying potential corrective measures. Because PMU data provides data from the period immediately before the event, during and after the event, it significantly speeds up the process of event analysis.

Phasor measurement technology currently provides the capability to monitor the following types of grid instabilities and can yield the benefits highlighted in italics:

- Angular separation analysis and alarming- enables operators to assess stress on the grid. *Measurement of phase angle separation allows early identification of potential problems both locally and regionally.*
- Monitoring of long-duration, low-frequency, inter-area oscillations; *accurate knowledge of inter-area oscillations could allow operators to adopt a power transfer limit higher than the limit currently in use if these oscillations are relatively low and well-damped.*
- Monitoring and control of voltage stability; *Knowledge of actual voltage stability can facilitate the transfer of more MW in an existing corridor.*

As emphasized in the KEMA study, a gap exists between observing an oscillation in real-time (and alerting grid operators) and translating this observation into a to-do-list for the operator on how to respond to the oscillation and correct the problem so it does not reoccur. This requires a training program that includes clear explanations for oscillations and real case studies of disturbances and diagnosis of factors that may have caused the disturbance. There is clearly a need for phasor applications that can provide diagnostic information on causes of an oscillation and actionable information.

The implementation of phasor measurement tools, methods and applications offer a potential means of significantly improving and benchmarking models. By providing precise, time synchronized measurements from various nodes in a power system, PMU deployments provides new opportunities for identifying errors in system modeling data and a fine-tuning power system models utilized throughout the industry for both on-line and off-line applications (power flow, stability, short circuit, optimized power flow, security assessment, congestion management, modal frequency, etc.). The use of phasor measurement for benchmarking and fine tuning dynamic and oscillatory modeling parameters is more complex and less advanced than for steady-state models. The use of improved oscillatory models for diagnosing problems and assisting operators in responding may be a promising approach.

The current data sharing, data communications and processing capabilities also restricts wider implementation and use of Phasor Monitoring and data analysis applications.[12] Data communications from the PMUs to the user interface requires robust data concentration, management and transfer capability that in many cases does not exist commercially today. While the basic data processing technology is available, the hardware and software to support the data collected, processed and transferred for these applications is still considered developmental. In general, vendors are not advancing rapidly in this area due to lack of immediate market applications. Users, on the other hand, are not pushing the vendors forward until some prototype PMU applications are proven.

The Energy Commission has provided funding support to the Electric Power Group and CERTS for the development and initial testing of a Real Time Dynamic Monitoring System (RTDMS) in cooperation with Cal ISO and DOE which collects and PMU data from 57 locations in the Western Regional electric grid and incorporates the phasor data applications listed above, including situation awareness information displays of interest to Cal ISO grid operators and reliability coordinators [13]. With DOE funding support, EPG is also developing and testing RTDMS and incorporating these phasor applications and situation awareness information displays in cooperation with transmission owners and reliability coordinators as part of the Eastern Interconnection Phasor project[14]. These cooperative RD&D initiatives in the east and western regions have demonstrated the value of PMU technology and these phasor applications for both post disturbance analysis and real time grid operations.

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12 Novosel, op. cit.

13 Eto, Joe, Bernard Lesieutre, Nancy Jo Lewis, (Lawrence Berkeley National Laboratory) Manu Parashar, (Electric Power Group) Jim Cole, Larry Miller, (University of California). 2008. *Real Time Grid Reliability Management.* California Energy Commission, PIER Transmission Research Program. CEC‒500‒2008‒049. http://www.energy.ca.gov/2008publications/CEC-500-2008-049/CEC-500-2008-049.PDF

14 Parashar, M. and J. Dyer (Electric Power Group) and T. Bilke (Midwest ISO); EIPP Real-Time Dynamics Monitoring System; February 2006; http://certs.lbl.gov/pdf/eipp-rt.pdf

As part of the current Energy Commission funded project, the evaluation of PMU measurements at SCE's Antelope substation to baseline performance and assess impacts of wind generation on:

- Reactive support and voltage regulation issues associated with wind energy from type 1 generators, and growing penetration of newer wind generators with fault ride-through capability;
- Prevailing small-signal stability and oscillatory concerns
- Future assessments of:

  –Post-transient behavior characteristics (e.g., impacts on capacity rating of major transmission paths)

  –Cal ISO frequency response performance (WECC Frequency Response Standard currently under development)

This research will complement the ongoing Wind Plant Modeling research being conducted by the National Renewable Energy Laboratory (NREL) as described in section 5.3.

These phasor measurement applications provide a foundation for an expanded research, development and demonstration effort that is focused on detecting sources of grid oscillations that are a major reason for the derating of the capacity of transmission pathways that will be used to carry renewable energy resources consistent with 20 percent, 30 percent and 50 percent RPS goals in the coming years. The focus of this RD&D effort, as discussed further in the next section, is to detect, diagnose and mitigate the impact of low frequency oscillations and, through improved operating tools, assist grid operators and reliability coordinators in the WECC to collaborate with power plant and transmission owners and load serving entities to eliminate these sources of grid oscillation. This RD&D effort is directly related and complementary to the Real-Time Congestion Management, Real-Time Optimized Nomogram Operating Tools, and Improved Renewable Generation and End-use Load Models research efforts described in subsequent sections of this report. Although these research efforts should initiated and managed separately, the results in one area will help to advance the knowledge that will be useful in the other area since they are all addressing the capacity derating issues.

As highlighted above, achieving the full potential of phasor measurement applications will require the involvement of vendors to work with Cal ISO, BPA, and system operators and reliability coordinators across the US to commercialize PMU hardware, software, data sharing, communications and data management technologies[15]. This report assumes that the research, development, demonstration efforts will continue to be supported by the electric power industry, DOE and other entities and the Energy Commission will continue to play its appropriate role in this effort. However, this report does not address these broader technology RD&D needs, except as they related to the phasor measurement applications discussed further in subsequent sections

15 Novosel, op. cit.

5.2.3 Gaps

In general, the RD&D gaps in this technology platform are in data collection, communication and management, and application development and demonstration. There are 3 major and interrelated RD&D gaps that need to be addressed to detect, diagnose and mitigate the impact of low frequency oscillations and, through improved operating tools, assist grid operators and reliability coordinators in detect, diagnose and mitigate the impact of low frequency oscillations and, through improved operating tools, assist grid operators and reliability coordinators in eliminating or significantly reducing these grid oscillations and voltage instabilities. Logically, these gaps are sequential in nature, namely the first gap must be successfully addressed before proceeding to address the next gaps.

The first gap is work with one or more organizations to research promising phasor applications for detecting grid oscillations and voltage instabilities and diagnosing the sources and causes. This research would logically build on the previous research summarized above but might involve other research entities and vendors.

5.2.4 Gap Filling Research

Short Term

Stage 4 efforts:

- Once progress is made in addressing the first gap, the recommended approach for addressing the second gap is Stage 4 development of a commercial grade-prototype of promising operator tools, including detection, diagnostic and visualization features that integrate with existing versions of an evolving RTDMS capability at Cal ISO and other WECC reliability coordinators. The desired timeframe for this Stage 4 effort is 2010 to 2011 or 2012; the details of this timeline will depend on timely progress in accomplishing the goals of Stage 3 and Stage 4.

Medium Term

Stage 5 efforts:

- The third gap is to demonstrate the desirable features of commercial-grade prototype version as part of a Stage 5 RD&D project. The desired timeline is 2011 to 2012 or 2013; the details of this timeline will depend on timely progress in accomplishing the goals of Stage 4 and Stage 5.

5.3 Real-Time Congestion Management

5.3.1 New Capabilities Addressed

A Real-Time Congestion Management RD&D Initiative was also recommended by the KEMA study as an important phasor application. This would seek to analyze phasor measurement unit (PMU) data at various locations along major transmission pathways within the western regional grid system using computer analysis tools to determine real-time transfer limits for these pathways (rather than conservative off-line limits), compare PMU data with these updated real-time transfer limits and use least-cost real-time dispatch models to increase transfer limits, if reliable power transfer margins are determined to present.

5.3.2 Current Status

The goal of a real-time congestion management application is to maintain real-time flows across transmission lines and paths within reliable transfer capabilities through security-constrained dispatch adjustments in a least-cost manner. The traditional approach for accomplishing this for grid operators is to compare actual flow on a transmission path against a Nominal Transfer Capacity (NTC) calculated by grid engineers in advance using an offline methodology. Such offline calculations are based on assumptions about thermal limitations, voltage limitations or stability limitations; whichever is most restrictive in a given case. The assumptions used in offline NTC calculations are often conservative and can result in excessive margins, leading to unused transfer capacity and lost opportunity savings in the dispatch process.

The KEMA study concluded that economic potential was significant. In the case of Cal ISO, congestion costs in 2005 was $250 million. In addition to direct cost of congestion management, congested transmission paths limit the amount of renewable energy resources that can be imported and delivered to load.

Based on discussions with industry representatives and research community, KEMA reported considerable support for research, development and demonstration of PMU-based, Real-Time Congestion Management by enabling improved calculation of path limits and path flows.

One potential approach identified in the KEMA report is to explore the feasibility of several approaches for using PMU data to validate and improve stability nomograms and improve voltage stability, such as being explored in the current RTDMS project being funded by the Energy Commission. An alternative, complementary approach for improving stability nomograms is discussed in Section 5.4.

A second approach is to use PMU data to improve the accuracy and quality of state estimation solution for real time transfer capacity (RTC flows) on major transmission paths and these results would flow directly into the real-time security constrained dispatch model on the EMS. With co-funding support provided by many utilities, Tennessee Valley Authority (TVA) and Entergy funding Areva to research the use PMU data to improve state estimation accuracy. In a separate project funded by the Energy Commission, SDG&E is exploring the use of PMU data to improve state estimation accuracy for purposes of improving congestion management. One major uncertainty is required level of PMU deployment to achieve desired improvement in SE solutions and online rating calculations.

KEMA recommended that the Energy Commission and WECC should seek additional targeted opportunities to improve congestion management through PMU applications, particularly on paths limited by voltage and dynamic stability constraints. In such cases, it may be possible to improve real-time congestion management process by a twofold combination of (1) improved path flow calculations and (2) increases in path ratings through real-time rating algorithms utilizing PMU inputs.

5.3.3 Gaps

There are 3 major and interrelated RD&D gaps that need to be addressed to improve congestion management through PMU applications, particularly on paths limited by voltage and dynamic stability constraints. Logically, these gaps are sequential in nature, namely the first gap must be successfully addressed before proceeding to address the next gaps.

The first gap is the need for promising analytical approaches to improve congestion management through PMU applications, particularly on paths limited by voltage and dynamic stability constraints. This research would logically build on the ongoing research and feasibility assessment results summarized above but might involve other research entities and vendors.

5.3.4 Gap Filling Research

Short Term

Stage 3 efforts:

- Develop promising analytical approaches to improve congestion management through PMU applications. The desired timeframe is as soon as possible (e.g. 2008) through 2010 or 2011. This effort should also include outreach and communication of promising project results to reliability coordinators and grid engineers that are directly involved in conducting analyses of the transfer capacity of major transmission pathways into California.

Stage 4 efforts:

- Development of a commercial grade-prototype of promising operator tools that improve congestion management through PMU applications, including visualization features, which integrate with existing versions of an evolving RTDMS capability or other grid operating information systems at Cal ISO and other WECC reliability coordinators. The desired timeframe for this Stage 4 effort is 2010 to 2011 or 2012; the details of this timeline will depend on timely progress in accomplishing the goals of Stage 3 and Stage 4.

Medium Term

Stage 5 efforts:

- Demonstrate the desirable features of a commercial-grade prototype version. The desired timeline is 2011 to 2012 or 2013; the details of this timeline will depend on timely progress in accomplishing the goals of Stage 4 and Stage 5.

5.4 Real-Time Optimized Nomogram Operating Tools

5.4.1 Technology Overview

Nomograms are operating tools used by grid operators to determine the amount of power that can reliably flow on each of major transmission lines that serve a major load center. One important example is the Southern California Import Transmission (SCIT) nomogram that is used to determine power flows on 5 major transmission paths into the Southern California region- http://www.caiso.com/docs/2002/01/29/2002012909363927693.pdf

The current generation of "static" nomograms is developed by power system planning engineers using the results of extensive manual engineering studies. Since only off-line *planning* data is available to these planning engineers, large security margins are added to the allowable power flows on these major transmission paths to account for possible variations in loads, generation and other un-predictable system conditions. Because of the static pre-engineered nature of these nomograms, it is not possible to adjust allowable transmission line power flows, renewable and conventional power generation levels and other grid control equipment parameters to optimize real-time grid performance objectives, including reliability, dynamic security, voltage, thermal, and numerous other parameters. Real time nomograms offer the promise of creating dynamic nomograms whose limits are based on the conditions of the grid in real time and would be expected to raise allowable power flows in a number of situations.

5.4.2 New Capabilities Addressed

Renewable energy imports on major transmission lines into Southern California and other regions, as determined by these operating nomograms, are lower than the thermal capacity rating of many of these transmission lines because of concerns about voltage and dynamic instabilities. There is a need for "real-time nomogram" operating tools that can enable grid operators to dynamically map and re-map (based on real-time system data updates) and extend (via optimization) the "Secure Operating Region" of transmission-line power flows and dynamic operating margins of the Cal ISO system (or any portion of it) relative to numerous grid performance optimization objectives, including reliability, security, voltage, thermal, and numerous other parameters.

This new "real-time optimized nomogram" capability would significantly increase the amount of power, including that dispatched from both renewable energy and conventional sources, into Southern California and other important regions.

Because of the basic physics of AC power flow, the inertial energy stored in large spinning machines (for example, a generator) that supplies the stored energy during periods of system disturbance (for example, loss of a generator) can impact dynamic stability of the power grid. Different types of generation technology provide different levels of inertia. For example, wind provides a low level of inertia compared to. a conventional fossil fuel generator. As the electric industry shows a greater dependency on renewable resources and the existing fleet of generating resources is either retired or utilized less, there may be a negative impact on the dynamic response of the California grid as well as the Western Interconnection.

As a consequence, there is a need for "real-time optimized nomogram" operating tools that incorporate the inertial characteristics of renewable and conventional power generation in determining and optimizing transmission power flows and other grid operating characteristics.

There are several promising new technologies, such as energy storage, FACTS, and DC transmission that offer the potential to significantly reduce the voltage and dynamic stability derating of major transmission paths. There is a need for "real-time optimized nomogram" operating tools that can optimize transmission power flows and other desirable grid operating parameters.

5.4.3 Technology Status:

There are existing power flow computer analysis tools that might be upgraded to add desirable real-time successive over relaxation (SOR) mapping, remapping, optimization and visualization features. A key requirement for a real-time operating tool is the need for fast computation speed in performing rapid optimization and ranking of available grid control options that can expand the Secure Operating Region.

5.4.4 Gaps

There are 3 major and interrelated RD&D gaps that need to be addressed to establish the new grid operating functionalities that can be provided by a new "real-time optimized nomogram" technology summarized above. Logically, these gaps are sequential in nature, namely the first gap must be successfully addressed before proceeding to address the next gaps. Technology RD&D actions address each of these gaps in a logical, sequential manner.

The first gap is the need to develop a computer analysis tool that has the capability to rapid AC power flow analyses and, most importantly, optimization of reliability, transmission line power flows, voltage stability, dynamic stability and other operating parameters of interest to grid operators and transmission owners.

The second gap is the need to demonstrate the capability of a promising rapid computer analysis and optimization tool, using real-time grid operating data, to improve the real-time operational performance of an important nomogram such as SCIT. This should include a comparison of the optimized SOR boundaries determined by this new model with conventional nomogram analysis methods used by grid operating engineers. If initial SOR optimization results are promising, the next step is to add mapping, remapping and visualization features of interest to grid operators.

The third gap is to develop and demonstrate the desirable features of commercial-grade real-time optimization tool, possibly applied to SCIT and other complex operating nomograms, to grid operators and to work with interested organizations in transferring this new capability to them.

If successful, then this new real-time optimized nomogram tool might be useful to transmission planners for evaluating the benefits of energy storage, FACTS, HVDC and other technologies. However, because of the potential of these technologies to increase transmission imports into SCIT and other regions, other RD&D actions may be taken to evaluate this potential. This new nomogram tool may be useful in conducting more detailed benefit analyses and facilitating their adoption by grid operators.

5.4.5 Gap Filling Research

Short Term

Stage 3 efforts:

- Develop a computer analysis tool that has the capability to perform rapid AC power flow analyses and, most importantly, optimization of reliability, transmission line power flows, voltage stability, dynamic stability and other operating parameters of interest to grid operators and transmission owners. The desired timeframe is as soon as possible but this timeline depend on the capabilities of existing computer analysis tools for rapid performance of the critical optimization function and other logistical factors.

Stage 4 efforts:

- Demonstrate the capability of a promising rapid computer analysis and optimization tool, using real-time grid operating data, to improve the real-time operational performance of an important nomogram such as SCIT.

Medium Term

Stage 5 efforts:

- Develop and demonstrate the desirable features of commercial-grade real-time optimization tool, possibly applied to SCIT and other complex operating nomograms, to grid operators and to work with interested organizations in transferring this new capability to them.

5.5 Ramp Forecasting with Renewable Resources

5.5.1 Technology Overview

The output from wind and solar generation can change dramatically, both up or down, in a very short period of time. These rapid changes pose a significant challenge to system reliability and to the grid operators, who must meet the North American Electric Reliability Corporation (NERC) and WECC Reliability Performance Standards. Better forecasting and planning mechanisms, especially on a micro-climate basis, will enable the Cal ISO to mitigate the operational problems that otherwise arise from rapid swings in generation or load, both up and down.

5.5.2 New Capabilities Addressed

With the addition of 4,500 Megawatts of new wind generation in Tehachapi in the 2010 timeframe, Cal ISO and other grid operators are likely to experience periods where electricity production from these wind plants will rapidly decline while simultaneously the load is rapidly increasing. Energy ramps as high as 3,000 MW per hour or larger may occur between 7 AM and 10 AM in the morning in the 2010 and larger ramps over the longer term, as progress is made in pursuing the 33 percent and 50 percent renewables goals. Fast ramping generation, such as hydro units, will be essential for the Cal ISO to keep up with the fast energy changes. There will be other periods, particularly in the winter months, where large pacific storms will impact the wind parks and their energy production will rapidly ramp up to full output.

The Cal ISO Renewable Integration study[16] recommends the development of a new ramp-forecasting tool to help system operators anticipate large energy ramps, both up and down, on the system. The longer the lead-time for forecasting a large ramp, the more options the operators have to mitigate the impact of the ramp.

The Cal ISO report also identifies the need for research to analyze the impact of large central station solar power intermittency in producing large energy ramps, within the context of anticipated wind energy ramps as well as load variations and distributed customer-side-of the-

16 CAISO Integration of Renewable Resources Report; September 2007; Transmission and Operating issues and recommendations for integrating renewable resources on the CAISO Control Grid

meter solar photovoltaic (PV), small wind turbines and other distributed energy resources.

Wind generation energy production is not typically scheduled in the Day-Ahead market. The potential accuracy of the Day-Ahead forecast for wind generation energy production is a very important component in deciding what other generation should be scheduled for the next day. If 3,000 MW of wind is forecasted for the next day, it is inefficient and costly to start up fossil fuel generation that will not be needed. The Energy Commission Intermittency Analysis Project (IAP) study[17] and other wind integration studies have pointed out the critical importance of Day-Ahead wind generation forecasts. Cal ISO concluded that the Day-Ahead forecast does not have to be 100 percent accurate to achieve substantial benefits.[18].

5.5.3 Technology Status

There exists today a wealth of methods for short-term prediction of wind generation. An excellent summary of the state-of-the-art in wind power forecasting, available at the following website: http://en.wikipedia.org/wiki/Wind_power_forecasting, is as follows: "Advanced approaches for short-term wind power forecasting necessitate predictions of meteorological variables as input. Then, they differ in the way predictions of meteorological variables are converted to predictions of wind power production, through the so-called *power curve*. Such advanced methods are traditionally divided into two groups. The first group, referred to as physical approach, focuses on the description of the wind flow around and inside the wind farm, and use the manufacturer's power curve, for proposing an estimation of the wind power output. In parallel the second group, referred to as statistical approach, concentrates on capturing the relation between meteorological predictions (and possibly historical measurements) and power output through statistical models whose parameters have to be estimated from data, without making any assumption on the physical phenomena."

Another excellent summary of the state-of-the-art in wind power forecasting is provided in the November/December 2005 issue of the IEEE Power & Energy magazine[19].

The state-of-the-art in wind ramp-forecasting tool that might be developed for use by Cal ISO and other grid operators might incorporate the output of physics-based models in combination with anemometer data at the wind farm site and data from the automated surface observing systems and Doppler radars at nearby airports allow expert forecasting firms to construct a reasonable understanding of atmospheric events associated with the large downward and

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17 Intermittency Analysis Project Final Report; Prepared by Intermittency Analysis Project Team; Energy Commission-500-2007-081; July 2007; http://www.energy.ca.gov/2007publications/Energy Commission-500-2007-081/Energy Commission-500-2007-081.PDF

18 CAISO Integration, op.cit.

19 The Future of Wind Forecasting and Utility Operation" - Mark Ahlstrom, WindLogics; Lawrence Jones, AREVA T&D; Robert Zavadil, EnerNex Corporation; and William Grant, Xcel Energy

upward ramps.[20]

5.5.4 Gaps

A Cal ISO goal[21] is to have a prototype of a ramp-forecasting tool ready in 2008 for testing and evaluation. The production version of the tool must be ready in 2009 to coincide with the expansion of the amount of wind and solar generation installed on the system. Key questions identified in the Cal ISO study include:

- How to accurately forecast ramps? What are the best-forecast sources and what meteorological data is required? Does weather and climatological database available from the commercial Weather Bank service provide sufficient forecast information with sufficient geographical granularity or do we need additional data and another forecasting service?
- Is a Doppler radar system needed in major wind-generation areas (e.g., Tehachapi) to see approaching weather fronts? Would sonic detection and ranging be a more cost effective approach? What has been the experience of others detecting major weather fronts?
- Who needs the ramp data: Real time operations? Scheduling Coordinators? Wind Generator Operators? Others?
- How far in advance do we need to forecast ramps? A few hours? Day-Ahead?
- How should the ramp information be made available to Real-Time operations?
- What are the specifications for a Ramp Planning Tool to assist the Operators in anticipating the dispatch notices that will be required to either start Quick-Start units or to shut down units?

One attribute of wind generation in California is that significant energy production occurs at off-peak periods, when load is minimum, creating an oversupply issue at certain times of the year, in addition to the dynamic operational issues associated with the intermittency of the wind resource. However, future PHEVs are anticipated to have expanded battery power for extended electric-only operation, and presumably they will largely recharge overnight when minimum loads traditionally occur. This situation creates a potentially synergistic relationship between wind and PHEVs, i.e., coordinating PHEV electric demand with wind generation in a "smart" infrastructure can mitigate impacts to the grid. In the simplest instance, PHEV load could be switched off to counter drops in wind generation (similar to demand response), and switched on as wind generation increases. This project will investigate the potential for this hypothesized synergism in California, and issues such as: data requirements and availability; the potential value of the service on a per-vehicle basis; infrastructure and communications requirements; potential integration with Smart Grid and Demand Response systems; estimation of the relative rates of growth of penetrations of wind generation and PHEV load; and potential

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20 John Zack- AWS Truewind; Optimization of Wind Power Production Forecast Performance During Critical Periods for Grid Management; presented at Windpower 2007 conference; Los Angeles; June 3-6, 2007; http://www.awstruewind.com/files/AWEA_Windpower_2007_Forecasting.pdf.pdf

21 CAISO Integration, op.cit.

costs and benefits of vehicle-to-grid supply should battery systems be developed that can accommodate it.

5.5.5 Gap Filling Research

Short Term

No independent RD&D action is recommended at this time.

5.6 Intelligent Grid Protection Systems

5.6.1 Technology Overview

Typical protection systems utilize digital relays individually or in combination to protect valuable assets, such as transmission lines or generators. Advanced relays incorporate PMU technology directly into the relay. Transmission lines may incorporate redundant primary relays and back up relays in complex relays designed to insure reliable action. Operation of these systems is programmed based on the expectation of a relatively normal operating configuration. However, under abnormal conditions, such as can occur during a fault, the relay system may operate, or fail to operate, in a manner which was not intended.

During major cascading blackouts, protective relays have either been implicated in increasing the severity of the blackout or of failing to slow or stop the spread. In the August 14, 2003 blackout on the East Coast and the July 2 and August 10 1996 blackouts in the West, zone 3 impedance relays played a major contributing role as well as many transmission and generation protective relays. In each of these blackouts, due to an unusual and unanticipated set of circumstances, the EHV transmission grid became configured in highly abnormal operational states that were not anticipated or studied by protection and system operating engineers.[22]

These protection systems are almost exclusively local in nature. Wider area protection systems – Remedial Action Schemes (RAS) or Special Protection Schemes (SPS) have been created to provide a variety of system protection actions. As these systems grow in scope and complexity, there is the increasing possibility of unintended consequences.

The term "intelligent protection systems" is not precisely defined and can be used to mean any of a variety of related concepts. For this report, the term is used to primarily describe protection systems which use phasor data and are adaptive, i.e. which can monitor conditions in real time, and "intelligently" adapt their operation to reflect actual conditions on the power grid. Ultimately, intelligent wide area protection systems can be seen as "protecting" the system by controlling its operation in such a manner as to prevent faults or instabilities from becoming large scale outages.

Major outages such as described here are sometimes referred to as "Extreme Events," because of the multiple contingencies that occur, and because they are beyond the ability of planning and operations engineers to foresee, and in many cases, to mitigate once they start. There is research currently underway to develop new methodologies for analyzing extreme events and test the methodologies; first in simple network systems, and next in larger, more complex and realistic

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[22] Stuart, Robert. (Stuart Consulting). 2008. *Scoping Study of Intelligent Grid Protection Systems.*

network systems, modeling the California grid and its western interconnections. The research will develop techniques to address the complexity of failures involving many components, and is intended to improve the state-of-the-art for such analysis and to provide both technical and policy participants with useful insights into the value of transmission investments for preventing such events. In addition it is expected that the research will provide better approaches to responding to extreme events to limit their impacts on the electric system and the California customers it serves. Key technologies that will come into play in mitigating extreme events include intelligent protection systems as described here, wide-area measurement systems fueled by phasor data technology (cf. sections 5.2 – 5.4), Smart Grid system restoration technologies (cf. section 5.7), probabilistic forecasting tools (cf. section 6.7), and physical controls to effectuate the needed islanding and protection strategies (cf. section 4.6).

5.6.2 New Capabilities Addressed

New Accommodation Dynamic Behavior Capability #3: To operate the grid in response to renewable power plant dynamic behaviors.

The increasing penetration of renewables with different types of dynamic behavior increases the risk of serious consequences in response to a transient event. Intelligent protection systems offer the possibility of improved mitigation of the consequences of a fault and reduced likelihood of a fault triggering a cascading blackout.

New Capacity Transient Stability Capability #3: To relax, or eliminate the need for, transient stability limits.

Special protection schemes are based on off line studies and are inherently conservative as they are based on worst case conditions. As a result, under normal operation, they must operate at levels that may be lower than necessary for conditions at the time. For transmission lines which are stability limited, better control, which intelligent protection systems potentially offer can mean a relaxation of stability limits and higher available capacity.

5.6.3 Technology Status

Virtually all hardware needed for intelligent protection schemes is commercially available. However every situation is unique and each situation requires a unique design. The general process begins with a concept, followed by simulation testing and specification of the required resources (communication systems, sensors, control elements, software, etc.). Implementation and testing would follow. While considerable research has been done or is currently underway, there have been no demonstrations of the technology. To date, no one has used phasor data to take automatic action in response to real time conditions to stabilize or protect the system.

There remain a number of questions to be answered. These include issues such as communications latency, the time delay associated with a communications link. For special protection schemes to operate in response to a transient event, delays in the range of hundreds of microseconds may be unacceptable in some systems. Other issues include transformer accuracy and determining actionable criteria and actions to be taken.

5.6.4 Gaps

There are numerous gaps to be filled before intelligent adaptive protection systems can be widely used. The scoping study by Stuart and Bose identified a number of these gaps. They include:

- Component performance requirements

  How fast and how reliable does a communication system need to be in particular applications? Are transformers accurate enough?

- Actions and alarms

  What is an actionable event? What action should be taken?

Once these issues have been resolved, there remains the need for demonstrations of the technology.

In the area of Extreme Events research, the results of the Phase 1 project currently underway may point toward further Phase 2 efforts to refine and extend the methodology, analytical tools and controls needed for mitigation of major outages. The objective of Phase 1 is to develop a deeper understanding of cascading outages by beginning with a simpler, hypothetical system to develop and adapt efficient mathematical techniques; in other words, to test the feasibility of the analytical approach. In Phase 2, the results of Phase 1 will then be applied to a complete network model for California, analyzing potential extreme events, with broader participation by California investor owned utilities and Cal ISO, who will help develop realistic initiating events and scenarios.

5.6.5 Gap Filling Research

Short Term

Stage 3 efforts:

- Complete the Extreme Events research project currently underway. Use the results to develop Stage 4 efforts to apply the technology to the California transmission system and its typical operating scenarios.

Stage 4 efforts:

- A credible demonstration program of the technology potential of phasor measurements. Stuart and Bose have recommended a specific project to be run in parallel with an upgraded RAS at the Southern California Edison Big Creek project. There are other viable projects, but this one has a unique set of circumstances, including availability of equipment and an existing planned system upgrade which make it particularly suitable.

Mid Term

Stage 3 / 4 efforts:

- Research and demonstration projects aimed at exploiting PMU technology to proactively manage transient stability from a wide area perspective before a major outage occurs.

- Research and demonstration projects aimed at exploiting PMU technology to proactively manage small signal stability from a wide area perspective before a major outage occurs.
- Research and demonstration projects aimed at exploiting PMU technology to proactively manage voltage stability from a wide area perspective.

5.7 Smart-Grid System Restoration with Distributed Renewable Resources

5.7.1 Technology Overview

Traditional utility electric power systems were designed to support a one-way power flow from the point of generation through a transmission system to distribution level loads. These systems were not originally intended to accommodate the back-feed of power from distributed solar photovoltaic, small-scale wind turbines and other distributed energy systems at the distribution level.

Current interconnection requirements for residential net-metered PV systems in California require that the system include a UL 1741 certified inverter (meaning that it has been tested to meet the Institute of Electrical and Electronic Engineers IEEE 929-2000, recommended practice for safe utility interface of generating systems) that will disconnect from the utility distribution if the voltage decreases or frequency deviation. Disconnect switches must meet the National Electrical Code's Article 690 on solar photovoltaic systems published by the National Fire Protection Association.

When the utility is able to restore electric service on the distribution circuit, the customer is normally responsible for realizing that the distributed energy system has been disconnected from the grid and taking action to restore normal operation.

The IEEE standards for the inverter, along with system design components such as a lockable disconnect switch, are necessary to prevent "Islanding." Islanding refers to a situation where the grid power is down and a customer's generator is still on, creating the potential for power to feed back into the grid. This would cause an unsafe situation for linesmen working on an otherwise non-electrified portion of the power grid. Owners of grid-tied systems should know that their system's anti-islanding design also prevents them from having power on-site when the grid goes down.

5.7.2 New Capabilities Addressed

Grid operators are concerned that manual restoration of power production by distributed renewable energy systems may not be workable approach when a significant amount of the customer end-use electricity load is supplied by these distributed systems. Based on discussions with grid operators and transmission owners there appear to be two interrelated needs:

- First, there is a need for customer-side-of-the-meter interconnection equipment that will permit the automatic restoration of the operation of distributed energy systems if the voltage, frequency and other operating characteristics of the electricity distribution system are within normal operating ranges.

- Second, there is a need for reliable information about the operating status of these distributed energy systems to be readily available to grid operators and utilities, within the overall context of customer loads that will be connected when service is restored. These information needs are one of the important evolutionary features of the smart grid.

5.7.3 Technology Status

The need for customer interconnection equipment that provides this first functionality is similar to the type of customer demand response technology that includes 2-way communications and control of customer equipment. The Energy Commission is actively involved in planning and funding RD&D on various demand response technologies[23]; more information about the current status of this research is available at the following website: http://www.energy.ca.gov/research/integration/demand.html . The Energy Commission has also performed a Load Management Standards Proceeding; more information is available at http://www.energy.ca.gov/load_management/index.html. DOE is also actively involved in planning and funding research on smart power grid; more information is available at the following DOE website: http://www.oe.energy.gov/smartgrid.htm.

To effectively manage a demand response program, distribution utilities will need information about the operating status of customer end-use equipment. It should be relatively easy to also include the operating status of customer-side-of-the-meter solar PV and other distributed energy resources as part of demand response information systems that are likely be established over the next 5-10 as demand response programs are commercialized by California distribution utilities.

5.7.4 Gaps

In view of the Energy Commission's commitment to collaborate with distribution utilities and Cal ISO to expand customer adoption of demand response programs, the only gap that exists is to make sure these functional requirements described above are incorporated into the evolution of demand response programs.

5.7.5 Gap Filling Research

No additional transmission-related RD&D actions are recommended at this time.

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23 Energy Commission Demand Response http://www.energy.ca.gov/research/integration/demand.html

CHAPTER 6: Transmission Forecasting and Planning for Renewable Resources

6.1 Technology Overview

6.1.1 Improved Models

Grid planning and operating decisions rely on simulations of dynamic behavior of the power system. Both technical and commercial segments of the industry must be confident that the simulation models and database are accurate and up to date. If the transfer limits are set using overly optimistic models, a grid operator may unknowingly operate the system beyond its capability, thereby increasing the risk of widespread outages, such as occurred during summer 1996 outages. If the models are pessimistic, a grid operator may be overly conservative and impose unnecessary restrictions on the transfer paths, thereby increasing the risk of power shortages in energy deficient regions. Therefore, having realistic models is very important to ensure reliable and economic power system operation. Because accurate end-use load models and renewable generation models are likely to have a significant impact on the capacity derating of major transmission paths carrying renewable energy into and within California, it is vitally important that these models accurate current conditions as well as future changes over the 2009 to 20030 time frames addressed by the 20 percent, 30 percent and 50 percent renewables goals.

6.1.2 Uncertainty Analysis and Probabilistic Forecasting Tools

Uncertainty is a persistent theme underlying virtually every aspect of the transmission planning and grid operations. Traditional power system analysis tools do not directly assess the many, inescapable uncertainties that are inherent in all models and in all data they on which they rely. Responsible users of these tools cannot ignore these uncertainties because they routinely have a major influence on the results.

Common uncertainties in power system analyses used in transmission planning might include estimates of load growth in time, by region and by end-use composition, potential location and generating capacity of wind, solar, other renewable and central station power generation facilities, retirements or upgrades of existing generating facilities, and likelihood that transmission facilities and substations will be approved and constructed in the future. Common uncertainties in analyzing grid operations might include weather impacts on load and renewable generation output, operational status of various transmission pathways, operational status of power generation facilities, possibilities of unplanned outages of generation and transmission equipment, and real-time actions of market players to maximize revenues or reduce costs in generation or utilization of power. This uncertainty has been compounded by the disaggregation of the vertical structured utility, deregulated power markets, and the increased size of the grid interconnections crossing state and national boundaries.

Transmission planning is subject to many stakeholder concerns that involve fundamental differences of opinion regarding the future. These differences are inevitable given the inherent uncertainty in assumptions regarding future needs and resource developments. Transmission planning and grid operations would benefit from tools that quantify the effects of uncertainty in ways that will better inform decision making or allow for more consistent treatment of different perceptions of the sources or magnitudes of uncertainty.

Probabilistic forecasting is a promising technique for evaluating and visualizing the impact of uncertainty in power systems analyses. It relies on using new computer analysis methods to calculate a probability distribution of the occurrence of an event rather than the estimating a specific magnitude of the same event, such used in deterministic forecasting methods. Both techniques try to predict events but information on the uncertainty of the prediction is only present in the probabilistic forecast.

One of the most common probabilistic forecasting approaches to uncertainty analysis in modeling is the Monte Carlo approach, which characterizes the uncertain parameters and inputs using individual or joint probability distributions. Combinations of parameters or inputs are randomly selected, and the evaluation of a large number of combinations yields a distribution of outcomes. Direct treatment of uncertainty is limited by computational power: A Monte Carlo simulation that takes into account all of the important dimensions of uncertain information in the models in question is not feasible. A whole field of inquiry is dedicated to addressing this computational burden by using advanced algorithms and models. The most common techniques attempt to approximate the result of the Monte Carlo simulation using a small number of judiciously chosen selections. An interesting alternative approach is to develop a very simple approximate model that accommodates both the uncertainty representation and the traditional Monte Carlo simulation.

6.2 New Capabilities Addressed

6.2.1 Improved Models

Many of the transmission paths into load centers, such the Los Angeles Basin, are operated at capacity lower than thermal limits because of concern about the transient, dynamic and voltage stability behavior of the generation and end-use loads are of significant concern to transmission system operators.

The WECC Wind Generator Modeling Committee concluded the wind turbine models that are currently used in transmission system planning and reliability analyses are known to be inaccurate, and do not represent the new generation of wind machines correctly. Incorrect or uncertain analyses of the impacts of wind farms on the grid will adversely affect both efficient planning and reliable operation of the California electric delivery system.

Moreover, although a vast amount of work has been done on end-use load modeling over the past 30 years (including two issues of IEEE load modeling recommendations and literally hundreds of technical papers world-wide), the WECC Load Modeling Task Force has concluded that load models in dynamic programs still do not represent load behavior observed in the western regional system under all system conditions. The sheer magnitude of the modeling of load components, the complexity of the load compositions and the hourly and seasonal change in loads in the real system, represents a challenge to load representation in power system studies.

As a consequence, there is clearly a need for improved power system models to be sure that the reliable rating of major transmission paths are not overly conservative, thereby permitting the increased import of renewable energy into these load centers.

To address these needs, the Energy Commission provided co-funding in 2007 for a Comprehensive Wind Generator Modeling project[24] in cooperation with the WECC, DOE and its National Renewable Energy Laboratory to develop wind plant level models, including the performance of various types and wind machines and associated interconnection equipment. This research and planned future is summarized in section 5.3. . The WECC Wind Generator Modeling Group (WGMG) and the WECC Modeling and Validation Work Group (MVWG) are providing technical review of major RD&D findings and project deliverables. This project is now completed.[25]

In a second project, the Energy Commission provided co-funding support in 2006 for the cooperative Load Research Program[26] with the WECC, BPA and SCE to develop improved end-use load models, with particular emphasis on the voltage and dynamic stability or residential HVAC equipment. The project team consists of Lawrence Berkeley Laboratory, Pacific Northwest National Laboratory, Southern California Edison and EPRI Solutions in conducting this research and developing the improved load models, performance analysis tools and data. The WECC Load Modeling Task Force and the WECC Modeling and Validation Work Group (MVWG) are providing technical review of major RD&D findings and project deliverables.

6.2.2 Uncertainty Analysis and Probabilistic Forecasting Tools

Access of Renewable Resources to the Transmission Grid

Meeting 20 percent, 30 percent and 50 percent renewables goals will require a substantial amount of new transmission development, as most large-scale renewable resources are located in remote areas rather than near the state's major load centers. Energy Commission IAP study concluded that, for the 2010 Tehachapi case, 74 new or upgraded transmission line segments are needed at a first order estimated cost of $1.2 billion plus $161 million for transformer upgrades and unknown costs for land use and right-of-way costs. The 2020 case would require 128 new or

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24 Wind Plant Modeling and Interconnection Users Group Scope; UWIG Utility Wind Integration Group; WECC Wind Plan Modeling Project; http://www.uwig.org/windmodelug.htm

25 Muljadi, Eduard; Abraham Ellis. (National Renewable Energy Laboratory). 2010. *Western Electric Coordinating Council Wind Generator Development.* California Energy Commission. Publication number: CEC-500-YYYY-XXX

26 Dmitry Kosterev (BPA); WECC Load Modeling Progress Update; WECC Load Modeling Task Force and WECC Modeling and Validation Working Group; March 2008; http://www.wecc.biz/documents/meetings/PCC/TSS/MVWG/2008/March/LMTF 2008-03 - Load Modeling Update.pdf

upgraded transmission line segments, with just over half (66) needed to serve increasing load requirements. For just the 500 kV and 230 kV additions, a first order estimated cost would be $5.7 billion. In addition, 40 new or improved transformers would be needed at an estimated cost of $655 million (excluding detailed land use and right-of- way costs).

Because of the importance of building new transmission facilities to meet RPS objectives and because of the challenges currently facing transmission planners and the major stakeholders involved in transmission planning, the Energy Commission asked CERTS to conduct a scoping study[27] to identify options for public interest RD&D that will improve transmission-planning tools, techniques, and methods. Based on interviews with key stakeholders, review of transmission-planning documents relevant to California, and independent analyses of the state-of–the–art in transmission planning tools and methods, CERTS reached two major conclusions:

1. The institutional challenges to transmission planning far outweigh the technical challenges. RD&D activities alone cannot resolve institutional challenges. For example, even with exact models, perfect forecasts, flawless power-flow tools, and ideal security criteria to address the many technical challenges, the planning process will remain subject to a host of non-technical stakeholder concerns and federal/state laws and policies.
2. However, research could focus on information and tools that facilitate the public debate necessary to reach consensus on major transmission projects. Two important research topics in this area would be: methods for readily accessible presentation of information and reliance on mutually agreed upon tools (which may not be necessarily the most technically advanced) that can be easily used by all stakeholders. Improving the level of discourse through advances in these two areas can help clarify the underlying differences of opinion and values that drive current debates and identify options that might effectively address stakeholders' concerns.

The status of development and application of probabilistic forecasting methods for transmission planning and the identification of major gaps, promising RD&D initiatives and timelines is discussed further in Section 6.5.

Easing Capacity Constraints on the Transmission Grid

In cooperation with Cal ISO, the Energy Commission has provided funding to EPRI[28] to explore the use of Monte Carlo-based probabilistic forecasting methods to analyze the impact of increased wind generation anticipated with California's goal of 20 percent Renewables Portfolio by 2010 on the volatility of short term and long term congestion costs and constraints on

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27; Joseph H. Eto, Bernard Lesieutre, and Steven Widergren, *Transmission-Planning Research & Development Scoping Project*; 2004 California Energy Commission, 500-04-061 http://www.energy.ca.gov/reports/2004-11-03_500-04-061.PDF

28 Lee, Stephen, 2008. *Probabilistic Transmission Congestion Forecasting.* California Energy Commission, PIER Program. CEC-500-2013-120 http://www.energy.ca.gov/2013publications/CEC-500-2013-120/CEC-500-2013-120.pdf

renewable energy imports on major transmission pathways into the state. This research analyzed the impact of significant uncertainties caused by load and generation forecasts as well as random unplanned equipment outages. Annual congestion costs on the California-Oregon Intertie (COI) path increased to $12 million in 2006 compared to $6.7 million in 2005. This research showed that the volatility of congestion costs and transmission import constraints due to wind generation will be magnified so improvements in congestion management could yield significant cost savings and help achieve the State's public goals.

The status of development and application of probabilistic forecasting methods for congestion management and the identification of major gaps, promising RD&D initiatives and timelines are discussed further in Section 6.6.

Accommodation of Renewable Energy Characteristics

Wind generation output varies significantly during the course of any given day and there is no predictable day-to-day generation pattern. As discussed in section 5.5, one major challenge to system operators is the availability and accuracy of Day-Ahead and Hour-Ahead wind generation forecast to ensure sufficient units are committed in the Day-Ahead and Real Time markets for the next operating day.

The Cal ISO also anticipates facing daily challenges to ensure adequate non-intermittent resources are available to meet multi-hour ramps, to accommodate changes in system load and wind generation. These challenges are compounded when combined with large hourly ramp changes on the interties and hourly generation scheduling changes.

The Cal ISO's power grid infrastructure and its operating procedures are designed for primarily traditional generating resources with predictable and dependable capacity with minimal dependence on intermittent resource. Interconnections of the intermittent resources such as wind power plants, which are not considered to have dependable capacity, create operational concerns for the Cal ISO grid operators. These concerns are expected to increase in the 2010 to 2030 timeframe as additional wind, solar and other renewable generation is integrated into the California Power grid to meet the 20 percent, 33 percent and 50 percent RPS goals.

As a consequence, Cal ISO is interested in exploring new grid operating tools that can assist grid operators to identify the impacts of intermittent renewables on the power grid operations and assist operators in avoiding disturbances and other emergency conditions which may result in cascading outages and ultimately blackouts. One promising approach of interest to Cal ISO for accomplishing this objective is the possibility of using pattern recognition and multivariate statistical methodology with a sound technical foundation that can exploit the available real-time data collected and stored in the control room facilities, such as Cal ISO's Energy Management Systems (EMS).

Extensive research by CIEE has determined that pattern recognition algorithms have been developed to find typical patterns and atypical events within complex data systems. [29] One example is the pattern recognition algorithms and computer analysis tools that have been

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29 Pattern Recognition Summary; http://en.wikipedia.org/wiki/Pattern_recognition

applied to digital flight data for commercial airlines.[30] These systems contain many sets of data with hundreds of variables being measured over time generally resulting in many gigabytes of data to be analyzed. Using statistical and mathematically based algorithms this software identifies atypical flights, along with identifying which flight parameters and which flight phases are atypical. These algorithms also cluster the flights into a finite number of distinct patterns. This allows the flight analyst the opportunity to focus on atypical flights, as well as the typical flight patterns discovered, removing the need to individually explore each flight separately.

There is growing interest in the power system engineering and operations community in exploring whether this approach could be applied in real-time grid operations, post-disturbance analysis and other applications, possibly using a combination of EMS (traditional SCADA) and phasor measurement data.

The status of development and application of probabilistic forecasting methods for real-time grid operations and the identification of major gaps, promising RD&D initiatives and timelines are discussed further in Section 6.6.

6.3 WECC Wind Modeling

6.3.1 Technology Status

In recent years, WECC has seen a significant increase in wind generation installed capacity, and this trend is projected to continue in the near future due in part to the aggressive renewables portfolio standards that have been established in the WECC footprint, particularly in California. As of the end of 2005, there were 4,500 MW of wind generation capacity installed in WECC, with some areas already at high levels of saturation. Modern wind power plants can be 300 MW or larger, and their dynamic performance has a significant impact locally and even at the regional level. As the installed and planned wind generation capacity continues to increase in WECC, better modeling of wind generators in transmission planning and system impact studies is needed.

WECC maintains a comprehensive database of dynamic models that all its members' use for system studies. These studies are routinely used to assess the performance of the interconnected transmission system, and to demonstrate compliance with applicable reliability standards. The results of those studies drive planning, operating and investment decisions. Currently, the WECC model database does not contain wind dynamic models; therefore, characteristics of wind power plants are ignored in large-scale planning studies. This is due to the limited availability of validated dynamic models for wind generators, particularly in the GE PSLF platform. A large set of models has been developed for the Siemens PTI PSS/E platform; however, a significant number of those models are proprietary to the manufacturers, and can only be accessed through non-disclosure agreements. In general, model development has been

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30 Ferryman, Tom; Power Grid Monitoring and Alerting System Adapting; Powerpoint Technical presentation NASPI Synchrophasor Meeting; May 7-10, 2007; http://phasors.pnl.gov/eipp_meetings.html

hampered by the rapid technological evolution of wind turbine-generators, and confidentiality concerns on the part of most manufacturers.

Even though there is industry consensus that wind generators can be classified in four basic categories, corresponding positive-sequence standard models do not yet exist. With only a few exceptions, the models that exist are proprietary and tailored specifically to each type of wind turbine generator. The lack of uniformity in study requirements and modeling approaches has resulted in a rather large number of distinct model versions. Until some model standardization occurs, and model access issues are overcome, WECC cannot incorporate these wind generator models in its dynamics database.

In June 2005, WECC convened the Wind Generator Modeling Group (WGMG) under the auspices of the WECC Modeling and Validation Work Group (MVWG) to develop a set of generic, non-proprietary wind generator models suitable for positive-sequence dynamic simulations. It is envisioned that four standard models are required to represent the basic types wind turbine generator technologies available in the market: conventional induction machines, wound rotor induction machines with variable rotor resistance, doubly-fed induction machines, and full converter machines. Although the standard models are being developed for use in the WECC, it is anticipated that the models will be embraced as the industry standard.

Large-scale planning studies require an equivalent representation of wind power plants. For most applications, this should consist of a station transformer, equivalent collector system impedance, equivalent generator unit pad-mounted transformer, and equivalent wind-turbine-generator. This representation is commonly referred to as a "single-machine equivalent." The dynamic models must therefore include plant-level controls that may be implemented, including voltage control and reactive power support, ramp rate control, etc. Some work has been done in this area, but clear procedures for deriving equivalent representation for wind power plants need to be developed and documented. The WECC Wind Generator Task Force (WGTF), a group that reports to the Technical Studies Subcommittee, has been tasked to develop guidelines for wind power plant load flow representation.

A required part of model development is validation. WGMG and WGTF plan to address this need in two ways: (1) identify, collect and analyze existing field data for both individual wind turbines and for wind power plants, and (2) install data acquisition equipment for passive (non staged tests) and long-term monitoring. The RD&D approach for accomplishing these goals include:

- Collect and monitor data from several wind power plants representing the four types of wind turbine models developed in this project.
- Validate the previously developed wind turbine models using data recorded from the wind power plants.
- Develop wind power plant equivalence modeling methodologies to represent the collector system in a large wind power plant with an equivalent single turbine representation or with a multiple turbine representation.

- Develop guidelines and recommended practices for wind turbine model and wind power plant representation.
- Widely disseminate the results by distributing reports through various professional organizations and through the use of published articles and brief informational notes on aspects of the project and accomplishments.

At a WVMG Meeting in Roseville, CA in November of 2007, the NREL project manager reported the following progress in accomplishing these goals[31]:

- Initial model prototypes for each WTG Type were developed;
- Type 3 model (doubly-fed asynchronous generators from any manufacturer) already implemented in PSLF and PSSE;
- Type 1 generic model prototyped and tested in PSSE;
- Implementation of the rest of the models to be completed by the end of 2007;
- Industry collaboration includes model users, model developers, manufacturers, project developers and professional groups including IEEE, Utility Wind Integration Group, Electric Reliability Council of Texas and others
- WECC guide describing recommended power modeling practices prepared and Draft presented to MVWG for comment
- Validation of the models is the next major task

6.3.2 Gaps

No significant RD&D gaps have been identified for this technology. This research is now completed. [32]

6.3.3 Recommendations

The Wind Plant Modeling Project, including the wind plant monitoring and model validation initiative is a very comprehensive effort that will yield significant modeling and wind plant interconnection standards benefits for Cal ISO and other grid operators and transmission planners. This research is now completed.

Moreover, representatives from California transmission owners and Cal ISO have expressed concern about how distributed solar PV systems are incorporated in end-use load models, including uncertainty about the voltage stability and dynamic stability issues. This is considered further in RD&D gaps related to Load Modeling in section 5.4.2. These industry

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31 Abraham Ellis (Public Service Company of New Mexico); Wind Generation Representation- WECC Modeling Efforts' UWIG Annual Meeting; July 2007; Anchorage, AK; http://www.uwig.org/Anchorage/Ellis-WECC.pdf

32 Muljadi, Eduard; Abraham Ellis. (National Renewable Energy Laboratory). 2010. *Western Electric Coordinating Council Wind Generator Development.* California Energy Commission. Publication number: CEC-500-*YYYY-XXX*.

representatives also discussed the potential need for research on the impact of fluctuations in the electricity output of large solar concentrator, flat plate and other types of solar systems on the Up and Down Ramps that might be experienced by grid operators. This is discussed further in Section 5.5: Ramp Forecasting with Renewable Resources.

6.4 WECC Load Modeling

6.4.1 Technology Status

A vast amount of work has been done on end-use load modeling over the past 30 years including two issues of IEEE load modeling recommendations and literally hundreds of technical papers world-wide. Yet the sheer magnitude of the modeling of load components, the complexity of the load compositions and the hourly and seasonal change in loads in the real system, represents a challenge to load representation in power system studies. Existing load models in dynamic programs still do not represent load behavior observed in the system under all system conditions.

In 2001, an "interim" composite load model containing a static part and a dynamic part (modeled essentially to IEEE load modeling recommendations) was developed and implemented in the WECC. This was a first of its kind region-wide implementation in North America in a NERC region. The static model load part is 80 percent of the total load and is comprised of existing static load data from the WECC members. The dynamic part is a default induction motor model for approximately 20 percent of the total load. This composite model is currently in use for all operation and planning studies. The model is designed primarily to capture the effects of dynamic induction motor loads for highly stressed North to South oscillatory flow conditions during summer peaks in the WECC. At the time of the implementation of the model, the WECC Modeling and Validation Work Group (MVWG) stated that the "interim" model should be replaced with a full-scale composite load model WECC-wide. The WECC Load Modeling Task Force (LMTF) was assigned this task in 2002.

The interim motor model currently in the WECC stability program does not capture the significant dynamic phenomena that have been observed in certain locations of the WECC. Of particular concern is the inability of the load model to represent a delayed voltage recovery from transmission faults, similar to those that occurred recently in Southern California. In this particular event, it took approximately 30 seconds for voltage to recover in reality, while the simulations predicted almost instantaneous voltage recovery. Similar events have been observed in Desert Southwest. Without a more realistic load model, it is not possible to evaluate the grid exposure to the stability problems and to design and implement appropriate solution schemes. Further work to the interim model is required also in the simulation of the power oscillations on the California – Oregon Intertie and other key interties in the WECC. Since accurate load models are required to assess the damping of power oscillations, the finalization of WECC Power System Stabilizer Policy is contingent on completion of successful load modeling work.

The goals of this WECC Load Research Program are to improve the dynamic load models, performance tools and data used by the Cal ISO, California's major utilities, BPA and other members of the WECC LMTF to research the impact of the dynamic performance of airconditioning equipment, adjustable speed drives, electronic equipment and other residential, commercial, industrial loads on voltage and dynamic stability performance of the western grid and develop an improved load modeling capability and associated performance tools and data that can be used by WECC utilities to reduce the exposure of the western grid to stability problems, establish grid operating limits and more effectively evaluate related transmission and distribution capital investment alternatives.

The WECC LMTF indicated that results of this Load Research Program would be used for the following purposes:

- Transmission planning and grid operating studies: setting path limits, constructing nomograms, designing remedial action schemes, etc.
- Post-disturbance studies: understanding what happened, improving model accuracy.
- Individual studies of: specific events, issues and operating conditions.

The interim results of this research were reported by WECC representatives at a joint WECC LMTF and WECC Modeling and Validation Working Group (MVWG)[33] and by the LBNL research director at the NERC/TVA Stability workshop on May 24, 2008[34]. They both reported that research was progressing well on the following 5 tasks:

- Air-conditioner modeling and testing
- Load composition analysis
- Solutions to voltage stability problems
- Load Monitoring
- Sensitivity Analysis

6.4.2 Gaps

The WECC Load Research project is a very comprehensive effort that will yield significant benefits for Cal ISO and other grid operators and transmission planners. With respect to the renewables integrations, this project should be very helpful in setting reliable transmission path limits that are more accurate and less conservative, and hopefully with more margin for increased imports of renewable energy.

The WECC, BPA and SCE have identified the need for additional Phase 2 research to further advance the development of these end-use models and to develop unit-level solutions for mitigating air-conditioner voltage stability problems. And, because of the likelihood of increased interconnection of distributed solar photovoltaic systems by residential, commercial

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33 Abraham Ellis (Public Service Company of New Mexico); Wind Generation Representation- WECC Modeling Efforts' UWIG Annual Meeting; July 2007; Anchorage, AK; http://www.uwig.org/Anchorage/Ellis-WECC.pdf

34 Bernie Lesieutre -UW Madison/LBNL; WECC Load Modeling Transmission Research Program- Overview; NERC/TVA Stability Workshop; May 24, 2007; http://www.nerc.com/docs/pc/tis/11_WECC_Load_Modeling_Research.pdf

and industrial customers in response to RPS initiatives, the WECC, BPA and SCE have identified the need for Stage 3 research that can accurately model the impact of these PV systems, as well as other distributed renewable systems, on the aggregated end-use loads, including their voltage and dynamic stability performance. In addition, as more PV and other inverter-based sources of distributed and renewable generation displace conventional generation of the rotating machine variety, the impact of reduced rotational inertia on the stability margins of the system needs to be studied.

6.4.3 Gap Filling Research

Short Term

- It is unclear at this time whether additional Phase 3 research, development and demonstration efforts will be needed, particularly as it relates to interconnection issues associated with distributed solar PV systems that may be identified in Phase 2.

Medium Term

- An assessment of the effects of reduced rotational inertia in the system is needed, as non-rotating and inverter-based renewables penetrate the system at higher levels, displacing conventional generation sources. This will require modeling of these systems in stability analysis tools, and running simulation studies to determine whether stability issues exist, and if so, what the potential solutions may be.

6.5 Uncertainty Analysis and Probabilistic Forecasting Methods for Transmission Planning

6.5.1 Technology Status

The CERTS Transmission-Planning Research & Development Scoping Project[35] provides an excellent description of the state-of-the-art in transmission planning tools and specific needs for research on information and tools that facilitate the public debate necessary to reach consensus on major transmission projects. Two important categories of research needs were identified:

1. Methods for readily accessible presentation of information; and
2. Reliance on mutually agreed upon tools, which may not be necessarily the most technically advanced, that can be easily used by all stakeholders.

The CERTS study concluded, "The issue of uncertainty, in both assumptions and analysis methods, emerged as a persistent theme in discussions of virtually every aspect of the transmission planning, evaluation, and approval process. Traditional tools do not directly assess the many, inescapable uncertainties that are inherent in all planning processes. Responsible users of these tools should account explicitly for imperfect information and forecasts using techniques such as multiple-scenario analysis. The entire process of transmission planning and evaluation would benefit from tools that quantify the effects of uncertainty or that allow for consistent treatment of different perceptions by different stakeholders regarding the sources or magnitudes of uncertainty."

[35] Eto, op.cit.

Based on interviews with key stakeholders and a review of the literature, the CERTS project team identified 17 potential transmission RD&D activities in the following six topic areas:

1. Support and extend the Transmission Economic Assessment Methodology (TEAM) under development by the California ISO
    - Market simulation and market-power analysis
    - Transport vs. direct current (DC) vs. alternating current (AC) power-flow analysis
    - Uncertainty analysis and techniques
    - Economic modeling and evaluation of cost of trade across market seams
2. Harmonize transmission-planning methods/approaches
    - Multi-scale models- coordinating among different tools and approaches
    - Formal integration of bus-level load forecasting with system-level load forecasting
3. Expand the scope and focus of transmission planning
    - Longer-term scenario analysis
    - Generation adequacy forecasting- technology choice and location
    - Demand-side alternatives to transmission
    - Integration of natural gas pipeline and electricity transmission planning
    - Macro-economic studies- economic growth, property values & value of reliability
4. Support regional transmission-planning activities
    - Common regional databases and information exchange
5. Enhance transmission-corridor assessment and planning
    - Transmission-corridor planning/assessment tools
6. Address leading technical issues in transmission planning
    - Probabilistic vs. deterministic reliability criteria
    - Voltage/reactive reserve modeling
    - Load modeling
    - Deliverability capability of a generating unit

The Energy Commission is also supporting research on Planning Alternative Corridors for Transmission Lines (PACT) with Southern California Edison. The objective of this three year project is to develop a web-based siting decision analysis tool that assists stakeholders in analyzing the environmental, cultural, visual, economic and engineering attributes of alternative corridors for transmission lines. This siting decision framework is intended to carry the energy siting process from preliminary site assessments and informal public participation, through the rigorous environmental assessment and formal public processes, and through the siting permit processes. The framework would facilitate the regulator's work on reviews, independent analyses, public reviews and hearings, and constructive feedback to proponents and the public—and offer the flexibility to rapidly correct, add, and resubmit a proposal.

The tool is intended to educate the public and decision makers on the technical merits and facilitates understanding of the tradeoffs between proposed alternatives. It allows stakeholders to evaluate scenarios that represent their potential different values.

Technical Advisory Groups consisting of stakeholders and potential model user organizations is providing input on important assessment factors, data sources, evaluation methods, and website functionality. A subset of several Technical Advisory Groups is testing the use of the model in evaluating alternative routes for 3 transmission projects.

Training sessions are being conducted in the use of the PACT web-based model and a public workshop is being scheduled for the 4th quarter of 2008.

6.5.2 Gaps

Although SCE has tested the existing PACT model framework in the narrow context of internal site screening for a local substation and power line, several model development issues need to be resolved before the application will be easy, user-friendly, and efficient to use. More comprehensive testing and development are required to resolve technical issues and expand the model's capabilities (i.e., sensitivity analysis and risk assessment) to fully realize its potential as a decision support system.

6.5.3 Gap Filling Research

Short Term

Stage 4 efforts:

The active participation of the Cal ISO transmission planning staff and other key stakeholders in identifying RD&D priorities and participating in key advisory and model validation components of one or more of the 17 research needs identified by CERTS is critically important.

Medium Term

Stage 5 efforts:

If PACT results continue to show promise, further development and testing of this model may be appropriate.

6.6 Probabilistic Forecasting Methods for Congestion Management

6.6.1 Technology Status

In 2006, the Energy Commission provided funding support to EPRI to develop a Probabilistic Congestion Forecasting tool which will provide the Cal ISO with the capability to look ahead for the next 24 hours and predict whether the system will be able to get through the day without running into critical operating constraints, such as line overloads and low voltages under credible contingencies and disturbances. If potential problems are predicted, the tool will enable the Cal ISO to simulate various import scenarios and find the best way to avoid such problems. For the summer of 2006, and future summers as well (until the resource adequacy problem of Southern California is resolved), having this tool would improve grid reliability and avoid potential blackouts.

As described in the EPRI final report, [36] this project has developed probabilistic models and most importantly specified how to accurately model the key input assumptions to derive valid confidence levels of the forecasted congestion variables. The model used a Monte Carlo simulation method to accurately model the probabilistic and physical relationships between generation dispatch, load demand, and the configuration of the transmission grid to mathematically predict the key operating constraints of line loading along critical transmission paths. It demonstrated the methodology using the equivalent model of the WECC system, with focus on the impact of such congestion on the California power grid and consumers. The mathematical models and the time frames of the simulation differ between the short term (24 hours) and the long term (10-20 years), and therefore two computer models were developed to address the two time frames. With these computer programs, each Monte Carlo simulation computes the power flow under one particular scenario about the uncertainties. Thus, thousands of Monte Carlo simulations are conducted to gain confidence about the variability of the forecasted results of transmission congestion.

Some key results from the short term Probabilistic Congestion Forecasting simulation are:

- Integration of wind power into system has a great influence on the forecasted congestions;
- Daily patterns of wind power which exhibit a high degree of variability and uncertainty will likely cause more serious congestions with greater uncertainty;
- More accurate minutes-ahead, hour-ahead and day-ahead wind forecasts will lead to less uncertainty of congestion;
- Forecasted congestion is also highly dependent upon load forecasting and the dispatch of generation and external purchases.

6.6.2 Gaps

To assist transmission planners in evaluating technology-related options for optimizing the import of intermittent wind and other renewable energy resources into Southern California consistent with the potential 33 percent and 50 percent RPS goals, it is recommended that EPRI develop a congestion management methodology based on the Community Activity Room approach.[37] The goal of this Stage 3 project would be to analyze and visualize the congestion management and other benefits of various options of combining intermittent wind energy, energy storage, demand side options, and transmission capacity additions with various mature and near-term technologies, e.g., power electronics for power flow control. With this method,

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36 Lee, op.cit.

37 EPRI Community Activity Room and Integration of Renewables; Energy Commission IEPR Workshop; July 31, 2008; http://www.energy.ca.gov/2008_energypolicy/documents/2008-07-31_workshop/presentations/EPRI_Integration_of_Renewables.pdf

innovative and synergistic combinations of these technologies would be synthesized and then evaluated so that comparisons can be made to assess the best alternative transmission infrastructure options for delivering the most and the best form of reliable wind energy into Southern California.

Future work should extend this study to look into the relationship between the confidence levels of forecasting congestion and the specific uncertainties, such as generator outages, higher penetration of renewable generation, demand response or management, generator siting, load growth, transmission forced outages and market prices, etc. The extended study results would provide information on how public policies may be improved so as to increase the reliability, economic effectiveness and environment contributions of the California electric power system that is in California's public interest.

In addition, the potential application of this Stage 3 project's methodology to provide a useful framework to enable a linkage between transmission congestion forecasting with the financial community to manage congestion through a risk management approach is extremely exciting and promising. The combined long term and short term Probabilistic Congestion Forecasting analyses are potentially capable of providing decision-makers a way to consider the transmission congestion cost, the transmission investment requirements, and the balance between congestion risk with the financial and investment risks together.

As the California Independent System Operator develops its Market Redesign and Technology Upgrade (MRTU), a comprehensive program that enhances grid reliability and fixes flaws in the ISO markets, an issue that has received significant interest is the potential effects of renewables on locational marginal pricing (LMP). LMP is driven by a number of factors including the price and the scheduling of generation plants. Dispatch schedules for conventional plants are somewhat predictable because of the economics of their dispatch and planned outages, although independent owners can create surprises for LMP outcomes. Intermittent renewable power plants might be expected to increase the volatility of LMP since their scheduling is dependent on the wind behavior as well as the plant economics. This speculation appears to be corroborated by recent experiences in European markets. The research that has been proposed to address this issue will measure the LMP effects for various scenarios of intermittent renewable generation – most likely wind – defined by behavior, location, and penetration levels. The research would also recommend ways to characterize wind in LMP calculations to model this effect and perhaps mitigate the issue. Wind forecasting technologies (see section 5.5.3) will play an important role in helping to minimize the volatility of LMP due to renewables.

6.6.3 Gap Filling Research

Short Term

Stage 3 Efforts:

- A congestion management methodology based on the EPRI Community Activity Room approach. This project would require that the Cal ISO and the California utilities provide technical advisory support and transmission infrastructure and operating data. This project will address one of the major barriers to achieving the RPS goal of 33 percent in 2020 described in the Energy Commission Integrated Energy Policy Report Update 2006- inadequate transmission infrastructure to connect remotely-located renewable resources with major load centers in Southern California.[38] This probabilistic forecasting and Community Activity Room technology has been tested and proven in two previous PIER projects involving Cal ISO[39]. It is recommended that this project evaluate the technical performance and potential benefits of applying advanced transmission technologies, such as FACTS, and compressed air and other energy storage technologies in achieving these RPS goals. Using FACTS will provide the capability to control the network impedances to maximize the utilization of existing transmission infrastructure.

- A probabilistic forecasting project to investigate what implications the probabilistic congestion forecasting results may have for energy policies aimed at encouraging reliable and economic electric power delivery in California. This project would require that the Cal ISO provide technical advisory support and transmission infrastructure and operating data.

Medium Term

Stage 3 Efforts:

- Investigation of the Impact of intermittent renewable generation on LMP as Cal ISO implements its Market Redesign and Technology Upgrade (MRTU) and renewables continue to penetrate the transmission system to high levels.

Stage 4 Efforts:

- Develop and validate a transmission planning model in the 2012 to 2014 timeframe, conditional on the success of the Stage 3 congestion management project based on the Community Activity Room.

6.7 Probabilistic Forecasting Methods for Real-Time Grid Operations

6.7.1 Technology Status

CERTS is in the early stages of exploring the use of the pattern recognition algorithms and computer analysis tools that have been applied to digital flight data for commercial airlines[40] for post disturbance analysis..

Cal ISO grid operations leaders have expressed interest in research that would explore the potential for using statistical pattern recognition methods for enhancing their real-time situation

[38] California Energy Commission; *2006 Integrated Energy Policy Report Update*; January 2007 Publication #CEC-100-2006-001-CMF http://www.energy.ca.gov/2006publications/CEC-100-2006-001/CEC-100-2006-001-CMF.PDF

[39] Lee, Stephen, 2008. *Critical Operating Constraints Forecasting – A Decision Support Tool.* California Energy Commission, PIER Program. CEC-500-2012-067 http://www.energy.ca.gov/2012publications/CEC-500-2012-067/CEC-500-2012-067.pdf

[40] Ferryman, op.cit.

awareness capabilities as well as enhance their ability to respond to situations that might adversely impact reliability, given the increasingly likelihood of increasing integration of intermittent wind, solar and other renewable energy resources expected in meeting California's 20 percent, 33 percent and 50 percent renewables goals.

The following summarizes one near-term operating scenario of interest to Cal ISO that might be the focus of research on pattern recognition methods applied to real-time grid operations. The Tehachapi Area is expected to have one of the largest installations of wind generation in the State of California. Over 5,600 MW of wind generation consisting of both traditional induction generators as well as the latest modern doubly fed induction generators with power electronics controls are planned for the Tehachapi Area. In addition, the Tehachapi has one of the largest water pumping operations in the world. Through pumping, water is elevated 3,000 feet to over the Tehachapi Mountains to serve the greater Los Angeles Area. The combination of large amounts of wind generation and large pumping operation at the Tehachapi Area is expected to severely tax the power grid in the Southern California area and is therefore selected for analysis in this research. A new 500 kV transmission system is planned for the Tehachapi Area. Through this research, it can be validated how this new transmission facility enhances the statistical distribution of the power grid parameters in the Tehachapi Area.

Cal ISO has expressed an interest in exploring how historical EMS and SCADA sampled data, which is generally collected around-the-clock with the resolution of every few seconds, might be used to develop statistical functions, metrics and indices which describe the reliability and other grid operating impacts of intermittent renewables as a function of specific renewable resource type and location. System wide impacts on the power grid might then be determined based on aggregation of the individual local impacts.

The Cal ISO has help discussions about the development of one promising statistical pattern recognition based on the monitoring the forward electricity market scheduling activities such as the Day-Ahead Market where 90 percent of the dispatches have been cleared might enable early prediction of the deviations of the power grid parameters from their normal distributions. Therefore, statistical metrics and indices might be identified which may be used to determine the need for procurement of location-specific resources such as ancillary services to rectify the deviating parameters of the power grid due to intermittent resources in the forward and real-time markets.

In a related but separate project, the Energy Commission is providing funding support to a project team led by Ian Dobson at the University of Wisconsin to research the possible extreme events, starting with the present operating conditions of the power system that might lead to a power system blackout is critical in reducing the blackouts in the future[41]. Traditional direct analytic approaches using N-1, or even selected N-2, contingencies do not even begin to provide the capability to analyze these cascading blackouts, which have been characterized as "N-20" contingency events. Performing extreme event analysis for an interconnection such as the western grid using the traditional approaches and the fastest computers in the U.S. is estimated for even an N-3 to take many months, and an N-4 analysis to take over a thousand years. Clearly the traditional analytical tools will not suffice for extreme event modeling. Hence there is a need to develop new and innovative methodologies to simulate power systems to address the extreme events using practical power systems and come up with remedial actions which will allow system operators to keep the power system away from collapse. This research is in its early stages and it is unclear whether statistical forecasting and other uncertainty analysis methods will play a central or supporting role in this project.

6.7.2 Gaps

Although a Google search indicates that lot of theoretical research papers have been published on the use of pattern recognition and probabilistic forecasting in power system analyses, often using simple 30 bus models of a generic representative power system, CIEE is not aware of any promising research that address the specific pattern recognition application of interest to Cal ISO highlighted above.

There appears to be a significant gap between the apparent need to explore the potential the application of statistical pattern recognition method for assisting Cal ISO grid operators in integrating significant amounts of intermittent renewable energy resources into the California electric system, without adversely impacting system reliability.

6.7.3 Gap Filling Research

Short Term

Stage 3 efforts:

- Research and bench scale testing of the use of pattern recognition for probabilistic forecasting of abnormal conditions for real time grid operations

Medium Term

Stage 4 efforts:

- Technology development and prototype testing of the above Stage 3 project, conditional on the results of Stage 3.

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41 Morgan, Mark, Ian Dobson, Ram Adapa, Benjamin Carreras, Vikas Dawar, Murali Kumbale, Rod Hardiman, Lorraine Hwang, Bernard Lesieutre, Janghoon Kim, Yuri Makarov, Nader Samaan, David Newman, and Siri Varadan. (Pacific Northwest National Laboratory, University of Wisconsin-Madison, Electric Power Research Institute, BACV Solutions, Southern Company, CIEE, University of Alaska – Fairbanks, and KEMA). 2011. *Extreme Events.* California Energy Commission. Publication number: CEC-500-2013-031 http://www.energy.ca.gov/2013publications/CEC-500-2013-031/CEC-500-2013-031.pdf

CHAPTER 7: Conclusions

Electric transmission is necessary for accomplishing the state of California's renewable generation goals. To fulfill its mission, transmission must achieve three broad objectives: (1) provide physical access for each new renewable power plant by extending new lines to each new plant site, (2) reliably accommodate any unique renewable generator behaviors, especially intermittency, and (3) increase the system's power carrying capacity to handle the additional electric power flows over existing pathways, and through interties and gateways, to reach the majority of customers located in the State's urban areas.

As the levels of renewable penetration grow, the traditional "build" solutions, i.e., investments in wires, towers and conventional system-support power plants, are being strained to meet these three objectives. Getting permits to build new or expanded transmission to provide new access or additional capacity is a lengthy process that usually exceeds the time it takes to site and build the renewable power plants by many years. Building additional capacity in urban areas, both for traditional generation for system support and transmission infrastructure is also increasingly difficult. At some level of renewable penetration, traditional "build" solutions won't do it alone.

As an alternative, new technologies can be deployed in the transmission system to endow it with expanded or new capabilities that will assist transmission in achieving its three broad objectives. New technologies can provide new renewable power plants faster access to transmission by putting new transmission lines in a better light, either by reducing their visual impact, or by providing a new way in which how to look at their value and impacts. New technologies can improve the ability of transmission to accommodate unique renewable generator behaviors, through a smarter and more flexible grid. Finally, new technologies can increase the power capacity of the grid by optimizing it for greater power flow, for example, by mitigating thermal and instability operating constraints.

This study identified about a number of such capabilities which, at a minimum, will make renewable integration easier and less costly, and ultimately at some higher renewable penetration level, will probably be required to achieve California's renewable energy goals by augmenting "build" solutions. Some transmission stakeholders have expressed the opinion that we are already at the level of renewable penetration in California where the capabilities enabled by new technologies will be required.

The list of candidate new technologies identified and associated with each capability in this study is long, and the cost of RD&D needed to close every technology development gap found would be substantial, especially for any one funding entity. Priorities need to be determined to select what technologies enable the most valuable capabilities and when.

In developing a portfolio of high-priority RD&D projects, one should keep in mind that many of the desired capabilities are enabled by systems or tools which are each composed of many technologies working together, each of which might be at a different stage of development maturity, adding another degree of complexity to creating an effective portfolio.

Technologies, and associated tools and systems, are developed and deployed in a framework of policies, markets, industry practices, and other technologies, including the existing infrastructure, which will affect their rate of development, their efficacy in addressing issues or opportunities, market penetration, and hence the RD&D strategies and make up of the RD&D portfolio.

Cost is a big factor in determining if and when a new technology, system or tool becomes used and useful. The cost of a new technology is usually higher than a competing established one, so faces a deployment hurdle. RD&D can often reduce costs of new technologies, and sometimes the costs of the competing existing "old" technologies increase. Incentive policies or deployment in niche markets can give the new technology, especially if it has, or enables, a strategic or high market or societal value, the advantage it needs to get into the market, and from that position increase its market share. The strategic value renewables have for combating global warming, and other societal, environmental and economic problems, will likely be a factor in determining the rate of market entry of new transmission technologies that enable renewable integration, and again affect the make up of a transmission technology RD&D portfolio.

Priorities determine what projects to include in an RD&D portfolio, and can mimic financial investment portfolios. An RD&D portfolio might have high-risk with high-payoff potential, be conservative, or be balanced with regard to risk/reward or short-, mid-, and long-term emphases. The priorities for an electric transmission RD&D portfolio for California should reflect consideration of the current and projected state and federal policies and regulations. They should also reflect the needs of the transmission and renewable energy communities of planners, owners, operators, and suppliers.

In this period of rapid change and growing uncertainty, these priorities should be frequently reviewed, but revised only after much deliberation and with a "cathedral-builder" perspective. Because most new technologies, especially for the electric transmission system, have taken many years to decades to be developed and commercialized, frequent changes in RD&D programs are counterproductive and wasteful.

Among the many new transmission technologies identified in this study to enhance renewable integration with the grid, a few can confidently cited as high priority.

For providing renewable plants faster access to the grid, new technologies that reduce the visual profile of a transmission line, such as underground lines, and that help the public and other concerned parties understand and communicate the values and costs of various alternatives, have high priority.

For accommodating the unique behaviors of renewables, those technologies that mitigate intermittency impacts, such as wind forecasting and real-time, on-line operator monitoring, visualization and analysis tools that help operators prepare for and react to problems; and energy storage and intelligent agents that help buffer the variable behaviors, are important.

For increasing the power flow capacity of transmission pathways, interties and gateways, priorities are given to technologies that (1) remove operational reliability constraints, such as real-time nomograms; real-time and wide-area monitoring, diagnostic and evaluation tools, especially those using phasor measurements; and power flow control devices; and (2) allow for higher current density flows or voltages, such as new transmission line materials or configuration designs.

Finally, important across all three objectives are technologies, such as probabilistic and statistical analytics, for improved planning under growing complexities and uncertainties.

GLOSSARY

Original Term	Acronym/Abbreviation
Bonneville Power Administration	BPA
California Independent System Operator	Cal ISO
California-Oregon Intertie	COI
compressed air energy storage	CAES
Consortium for Electric Reliability Technology Solutions	CERTS
convertible static compensator	CSC
Department of Energy	DOE
Electric Power Research Institute	EPRI
electromagnetic field	EMF
fault current controllers	FCC
first generation	1G
flexible AC transmission systems	FACTS
gate turn off {thyristor}	GTO
high voltage direct current	HVDC
high-density polyethylene	HDPE
high-temperature superconductor	HTSC
high temperature, low sag	HTLS
interline power flow controller	IPFC
Intermittency Analysis Project	IAP
Lawrence Berkeley National Laboratory	LBNL
Load Modeling Task Force	LMTF
locational marginal pricing	LMP
Market Redesign and Technology Upgrade	MRTU
Modeling and Validation Work Group	MVWG
National Electric Energy Testing Research and Applications Center	NEETRAC

National Renewable Energy Laboratory	NREL
nominal transfer capacity	NTC
North American Electric Reliability Corporation	NERC
Pacific Gas and Electric	PG&E
Pacific Northwest National Laboratory	PNNL
phase monitoring unit	PMU
photovoltaic	PV
Planning Alternative Corridors for Transmission Lines	PACT
plug-in hybrid electric vehicles	PHEV
radio frequency interference	RFI
Real Time Dynamic Monitoring System	RTDMS
real time ratings	RTR
remedial action schemes	RAS
renewable integration	RI
Renewables Portfolio Standard	RPS
research, development, and demonstration	RD&D
right of way	ROW
San Diego Gas and Electric	SDG&E
second generation	2G
Southern California Edison	SCE
Southern California Import Transmission	SCIT
special protection schemes	SPS
static series synchronous condenser	SSSC
static synchronous compensator	SSC
static VAR compensator	SVC
successive over relaxation	SOR
superconducting magnetic energy storage	SMES
Supervisory Control And Data Acquisition	SCADA

thyristor-controlled phase shifter	TCPS
thyristor-controlled series capacitors	TCSC
unified power flow controller	UPFC
voltage source converter	VSC
Volt-Amp Reactive	VAR
Western Electricity Coordinating Council	WECC
Wind Generator Modeling Group	WGMG

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Appendix A:
Grid 101, Basics of Grid Engineering Principles

Introduction

The purpose of this paper is to give non engineers with at least a high school science background a simple high-level overview of the electric transmission system, its basic components, and ultimately a general understanding of the issues and challenges that arise and must be addressed whenever a new generating plant, renewable or otherwise, is connected to the system.

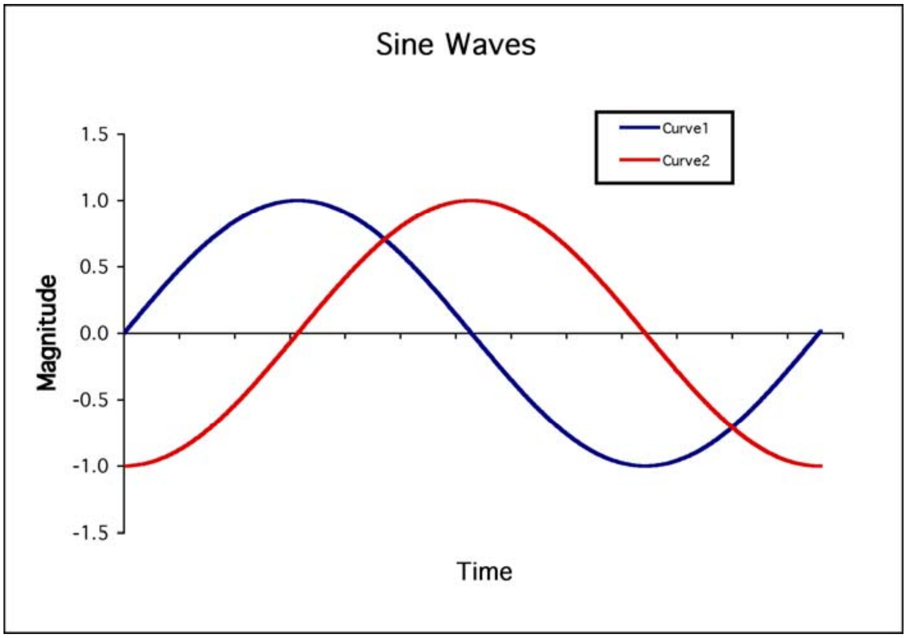
Basic Quantities in the Power System

Voltage

Also called "electromotive force," voltage is the electric "pressure" developed within energy sources that "pushes" free electrons to move inside conducting materials (e.g., metals) and semiconducting materials (e.g., silicon-based electronic chips). Voltage is commonly expressed in volts (denoted as V) and thousands of volts (kilovolts, or kV). In the US, the highest voltage level is 1100 kV; the lowest is 120 V at the common household outlet.

Voltage is developed in the power system primarily by rotating electromagnetic machines called synchronous generators (see Generators, above). Because the voltage is developed by rotating a coil of wire within a stationary magnetic field, the voltage that is produced varies as a sine wave (see Figure 1). This is called alternating current (AC). If power electronics are used to convert the alternating current to a constant, non-varying current, this is called direct current (DC). AC is the predominant type of electrical power in the US, although DC lines are becoming more common.

Figure 1. Voltage Sine Waves



Frequency

Curve 1 in Figure 1 shows one **cycle** of voltage: the voltage goes from zero to maximum, to minimum, and back to zero, corresponding to one rotation of a generator. The North American power system uses a standard frequency, symbolized as the letter f, of 60 cycles per second, measured in units of Hertz, or Hz. This number evolved over time, and primarily was derived from the rotating speed of steam turbines (60 Hz = 3600 rpm rotational speed). System operators must maintain system frequency as close to 60 Hz as possible, and also must correct for frequency-time error accumulation, called area control error (ACE). The main issue with frequency is that if the system deviates, even for a short time, from 60 Hz, the large steam turbines on the system will be damaged by excessive vibrations. Protection systems will trip generating units or loads from the system to prevent such occurrences.

Current

Current is the flow of electrons as a result of the imposition of voltage on conducting materials. It is commonly measured in amperes (aka amps, denoted as A), and symbolized by the letter I. Since electrons have a negative charge, a "positive" current is opposite to the actual flow of electrons. Current can only flow in a completed circuit, i.e., an electrical connection from the source to the load, returning by a "ground" connection; a ground connection can be either a separate electrical path such as a wire or cable, or through the actual ground of the earth.

Impedance

All materials (aside from superconductors) provide some impediment to the flow of electrons. The degree of this quality is termed impedance, symbolized by the letter Z, and is measured in ohms (denoted by Ω, the Greek symbol for omega). Impedance has two components: resistance and reactance. Resistance results from the basic characteristics of the material. Metals such as silver, copper and aluminum have very low resistance and are called good "conductors." Materials such as silicon and gallium, used in electronic chips, provide a measured amount of impedance when doped with certain other elements, and are collectively termed "semiconductors." Materials with very high impedance such as glass, polyethylene, pure water, etc., that allow little or no current to flow are called "insulators." Generally, in the power system, conductors are used where current needs to flow with maximum efficiency, semiconductors are used in electronics and other devices for controlling current flow, and insulators are used where it is necessary to prevent the flow of current, e.g., from transmission lines which are at high voltage, to the transmission tower which is at ground (zero) voltage.

The reactance of a material is mainly a function of how the material responds to the frequency of the voltage applied to it. Inductive reactance produces a current component shifted 90° behind (lagging) the resistive current component; in Figure 1, Curve 1 could conceptually represent the inductive current component that lags 90° behind the resistive current component represented by Curve 1. Capacitive reactance would produce a current component shifted 90° ahead of (leading) the resistive current component.

Power

Power is defined as the rate at which energy is expended or work is accomplished. In an AC electric power system, total power (or "complex power") consists of real and reactive components. Since these components are 90° out of phase with each other, the magnitude of the total power is the algebraic sum of the components.

Real Power

The "real" power expended in a material that results in "work". It is the product of the current times the voltage across its resistance. It is expressed in watts (W). Heat, light and physical movement are typical manifestations of real power resulting in work.

Reactive Power

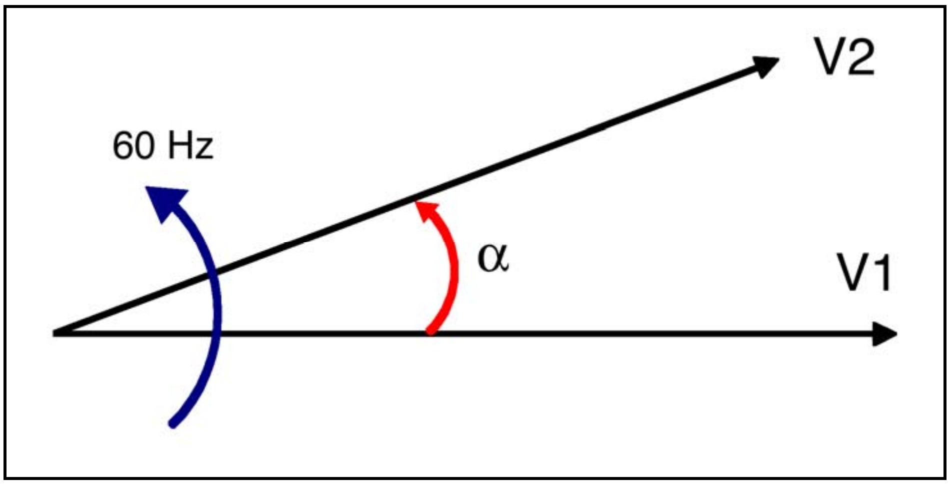
Reactive power is the product of the current times the voltage across a reactance. It is expressed in volt-amperes reactive, or VARs; also kVARs and MVARs. Reactive power basically represents the energy used to set up and maintain the AC electric and magnetic fields in the electric system components; it does not result in work accomplished, in and of itself. But the electric and magnetic fields are the mechanisms by which electric power is generated, transmitted, and consumed.

Phase Angle

The phase angle of voltage or current derives from the voltage waveforms of the generating machines on the system. Most generators are rotating machines that produce sinusoidal voltages with a frequency of 60 cycles per second. If one machine produces a voltage that peaks one quarter of one cycle behind another, the phase angle between them is 90º (e.g., Curve 1 vs. Curve 2 in Figure 1). Phase angles of voltages and currents in the system will vary throughout the system, and are an important measure of power system stability.

When current, voltage and power are represented as phasors, they are depicted as rotating around a fixed point, like hands on a clock. In this representation, the angle between any two quantities is the phase angle. In Figure 2, the voltages V1 and V2 are separated by the phase angle α; the phasors rotate counterclockwise at a frequency of 60 Hz.

Figure 2. Electrical Quantities Represented as Phasors

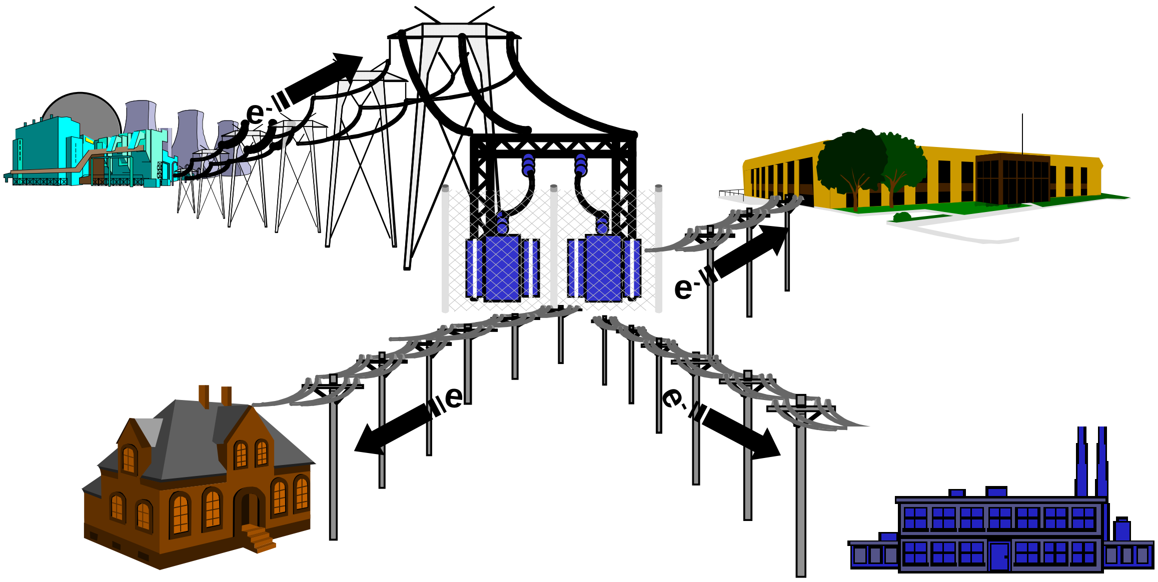


Description of the Electric Power System

Overall Structure

The electric power grid is a complex system with many components. Its purpose is to generate electric energy and deliver it to customers in a safe, reliable and cost-effective manner. Figure 3 gives a simple view of its basic structure; in reality, there is a large number of each type of component, resulting in an extended network of interconnected elements, i.e., a “grid.” Historically, electric energy was generated primarily at large plants, transmitted in bulk over high-voltage transmission lines, and then distributed over lower-voltage lines to customers; the system was termed “vertically integrated” because one company (usually a utility) owned and operated the entire system. State and Federal agencies oversaw the utility’s operations, and set the rates the utilities could charge the customers.

Figure 3. General Structure of the Vertically-Integrated Power Grid



In recent years, industry restructuring led to the substantial divestment by utilities of some of their generating plants, and the emergence of a competitive energy generation business with independent companies owning and operating much of the generation. Transmission and distribution businesses (which are sometimes separate) are run by utilities or by regional transmission companies. Further, smaller generating plants and customer-sited technologies such as photovoltaics (PV) and cogeneration have proliferated on the distribution system. The emphasis on climate change has resulted in substantial new energy generation from renewable sources. The result is that the structure of the electric grid is becoming increasingly more complex, with significant new planning and operating challenges.

Generating Plants

Plants that generate electricity come in many sizes, and employ a variety of fuel sources and technologies. The main types are described as follows:

Thermal

Thermal plants employ some type of combustion process, usually based on fossil fuels (coal, oil, natural gas), to heat steam in a boiler that is then run through a turbine, providing mechanical power to spin an electrical generator. The steam turbine is called a **prime mover**, meaning it is the device that provides the mechanical power to drive the electrical generator, and the generator thereby produces voltage and current output. Power output for a thermal generating plant can be as high as 1000 MW for a single unit. Steam turbines can be single-stage (one steam cycle) or two-stage (output of a high-pressure turbine is run through a second, lower-pressure turbine). Two-stage turbines are generally much more efficient than single-stage, and most new natural gas-fired plants are of the two-stage variety. Issues relating to large thermal plants include:

The start-up and grid synchronization process can take hours, meaning they can't be used for quick response if they are not already on the system.

After shutting down, a certain amount of time must be allowed for cool-down before firing the unit back up.

They are most efficient, and have lowest emissions, when operated near their maximum output. Fuel consumption and air emissions increase during cycling operation.

Cycling (varying their output as a function of load, for example) creates wear and stresses on the turbine-generator components, and if excessive can lead to additional maintenance needs, lower reliability, or premature failure.

They have a large rotating inertia due to the mass of the components. This is a critical parameter for system stability considerations (see below).

Combustion Turbines

Combustion turbines are basically large versions of aircraft jet engines, using either liquid or gaseous fuel; the expansion of the combusting fuel inside the turbine itself drives the turbine, usually a single-stage type. Output is typically in the 25 to 300 MW range. They are used mainly where fast start-up is required, usually in peak loading situations, and for standby generation when other generation is not available. Combustion turbines are generally much less fuel-efficient, and have higher emissions, than thermal plants.

Microturbines are a special type of combustion turbine, being fairly small (about 10 to 200 kW). They are designed to run on low-pressure natural gas, and are used in small commercial installations to provide backup power, or in a cogeneration (combined heat and power) application. They can also be adapted to run on methane in biomass plants (see below).

Fuel Cells

A fuel cell uses hydrogen for fuel, combining it with oxygen to produce electric energy in a chemical reaction, with only water vapor and heat as byproducts. In the electric system, fuel cells can be used as peaking units, particularly in substations with space constraints, such as those in congested urban areas. The main issues with fuel cells are that the installed cost is high, hydrogen is not a cheap or emissions-free fuel to produce (mainly being derived from natural gas), sizes are still relatively small for utility applications, maintenance requirements are significant, and longevity of internal components needs to be improved. The power produced by a fuel cell is DC, which must be converted to AC via power electronics, i.e., an inverter.

Engines

Piston-driven internal combustion engines that run on gasoline, kerosene, diesel fuel or natural gas, driving an electrical generator. They can be as large as several megawatts. Mostly used in peaking, standby or emergency generation, or as station power in large power plants to provide power to auxiliary equipment during plant startup.

Hydroelectric

Hydroelectric (hydro) plants typically consist of a dam on a river that produces a reservoir of water, a penstock (large pipeline) to route the water to a low-RPM turbine, and an electrical generator coupled to the turbine. Output is dependent upon sufficient water availability. Issues relating to large hydro plants include:

- The mechanics of the reservoir-penstock-turbine system can impose some operating restrictions.
- Generation of power must be coordinated with other uses, such as water demands from cities and agriculture, flood control, recreation, etc.
- Siting of hydro plants is highly dependent upon favorable geographic conditions.

"Run of the river" hydro plants are typically small turbines placed in the current of a river, and function essentially like wind turbines, producing electricity from the flow of water, and usually connected to the distribution system.

Nuclear

Nuclear plants use uranium-based fission to heat water, which is then run through a heat exchanger to heat water for a steam turbine. Aside from the fuel process, nuclear plants function essentially the same as fossil-fired thermal units from the perspective of the grid. They are most cost-effective when base-loaded.

Renewable Generation Plants

The following generating technologies are called "renewable" technologies because they use naturally occurring energy sources and not consumable fuels:

Wind

Wind turbines use propeller blades driven by the wind to spin an electrical generator. Most older wind turbines use induction generators, with pitch control of the blades to match the electrical output of the machine to the grid. Modern wind turbines use electronic systems to convert the AC power to DC, then back to AC at 60 Hz for injection into the grid. This allows the wind turbine to spin as the wind dictates, while providing proper electrical synchronization with the grid. One of the most cost-effective renewable technologies, wind power is competitive with most large-scale generating plants on a cost-per-kW installed basis. Wind plants can be built off-shore as well as on land. Issues with wind power are that the output is highly unpredictable, non-dispatchable, and intermittent (i.e., its output varies as a function of time), and it does not correlate well with the electrical system peak demands, creating integration problems with the electrical grid. Also, its siting is highly location-dependent.

Photovoltaic (PV)

Photovoltaic systems use semiconductor-based panels to convert sunlight into DC current; an inverter (DC-to-AC converter) produces ac power for injection into the grid. Issues with PV include cost, which on a per-kW basis costs several times what conventional generation costs to build, due to the high capital costs for the silicon solar cells and the electronic conversion equipment. Its correlation with system peak load is fair, approaching 70 percent in some locales, but is also characterized by a degree of intermittency. PV systems range from 1 to a few kW for residential systems, to several MW or more for commercial plants.

Solar Thermal

Solar thermal plants use mirrors to concentrate the sun's rays to focus heat into a thermal medium, such as water or molten salt. The heat is used to run a steam turbine, similar to other thermal plants. Usually requires a lot of real estate, and a source of water for cooling.

Geothermal

Geothermal plants typically inject water into wells drilled into heated rock layers in areas with geothermal potential. The water turns to steam, running a steam turbine. Reasonably cost-competitive, but highly location-dependent.

Biomass

Biomass plants make use of decomposing organic material, capturing the methane that is produced to use as fuel in a combustion turbine, such as a microturbine or natural gas engine. Typically they will generate on a continuous or base-load basis, but have more flexibility for peaking and cycling, similar to conventional combustion turbines.

Other Renewables

Other emerging renewable technologies include harnessing tidal power, and ocean thermal energy conversion (OTEC), which uses the thermal differential between deep ocean water and the surface to generate energy.

Transmission Lines

A transmission line is an electrical connection for the transport of bulk power over long distances. Its traditional applications are to deliver power from large power plants to load centers, and as connections between utilities or regions for the exchange or economy transport of power. Voltage levels are typically 50kV to as high as 1100kV, and length can be up to a hundred miles or so. The two basic types of transmission lines are:

Overhead: Stranded, bare aluminum or aluminum/steel cables, suspended by insulators from steel lattice towers or wood poles. Issues that can lead to difficulty in siting overhead lines include:

Visual aspects: Steel towers and cables are considered unsightly, especially against the backdrop of forests or mountains.

Audible noise: 60Hz hum and corona discharge (surface sparking of the conductor).

Radio frequency interference from corona discharge.

The safety hazard posed to migratory birds and aircraft.

External electric and magnetic fields (EMF). While most studies have not shown any evidence of harmful effects from exposure to AC magnetic fields, electric fields can induce annoying static electric effects in humans and animals; this is not usually an issue with lines that maintain proper clearances above people and buildings.

Environmental impacts from construction, disturbance of habitat and groundwater, etc.

Acquisition of rights to the land over which the line will be constructed (the "right-of-way").

Acquisition of permits required for construction, from all the legal entities having authority over the rights-of-way.

Overhead lines have been known to cause fires, and to be vulnerable to damage by fires.

Underground: Copper wires, encased in an insulating material such as oil, oil-impregnated paper or polyethylene, inside a pipe-type enclosure, and buried in a trench under backfill material. The public generally views underground lines as having far fewer negative impacts than overhead lines, although there are still some issues:

Construction costs for an underground line can be up to 10 times the cost of an overhead line of the same capacity, and construction can take much longer.

The biggest impacts will be disturbance to the environment in the immediate vicinity of the trench during construction, although it will be temporary. Also, the insulating oil or gas in the conduit can leak into the surrounding environment.

Access to, and maintenance of, underground lines is generally more difficult than for overhead lines, resulting in somewhat longer and more costly outages for underground lines.

Substations

A substation is a connection and control point for transmission lines and generating plants. It connects one transmission line to other lines for the routing of power, has transformers to step down the voltage to transfer power from one voltage system to another, and has protection and control devices that fulfill various operating functions. Its components will include: bus bars, circuit breakers, transformers, switches, metering devices, instrumentation, and voltage support devices such as capacitors. There is usually a building housing the instrumentation and control equipment.

Transformers

A transformer is an electromagnetic device that changes the voltage from one level to another. It typically consists of an iron core, around which copper wires are wound. The power is transferred from one coil to the other in proportion to the number of turns of wire in each of the coils, through the coupled magnetic fields of the transformer. Major types of transformers include:

Generator Step-up: Matches the output of a generator (typically 10-15 kV for large generators) to the voltage of the transmission line.

Transmission: Steps the power down from a high voltage network, e.g., 500 kV, to a lower one, e.g., 230 kV.

Phase-shifting: Has specially-designed core and windings to shift the phase of the voltage from one to the other, but usually not the voltage itself. Used to control the flow of power from one line to an adjacent line.

Distribution: Steps the power down from a transmission voltage, e.g., 230 kV, to a distribution voltage, e.g., 21 kV.

Distribution: Also refers to transformers used on the distribution system, i.e., at voltages below 50 kV on (mostly) radial, not networked, systems.

Switches, Relays, and Circuit Breakers

Switches are mechanical devices used to reconfigure lines and substations, typically when the lines are not energized, although some switches are designed to interrupt normal load currents reliably. They can be either manually-operated via a lever pulled by a lineman, or motor-operated remotely by operator command.

Circuit breakers are automatic devices that are designed to interrupt fault currents to protect expensive and vulnerable equipment, such as generators and transformers. Fault currents are typically several times higher than normal load current. Circuit breakers operate via a signal from a relay.

Relays are electromechanical or electronic devices that respond to measurements from sensors, typically voltage and current transducers (CTs and PTs), to send a signal to a circuit breaker to operate. Relays are programmed to detect faults (short circuits), low voltage conditions, out-of-phase conditions, harmonics, and other abnormal system conditions.

The combination of sensors, communications, relays and circuit breakers for a specific purpose to guard against system failures is called a protection system. There are a number of different types of protection systems in use in the electric grid. The more complex systems are referred to as special protection schemes (SPS) or remedial action schemes (RAS).

Capacitors and Inductors

A **capacitor** is a device consisting of conducting plates separated by an insulating layer. When AC voltage is impressed on a capacitor, the current flowing in it is +90º out of phase with the voltage. In Figure 1, the current in a capacitor could be conceptually represented by Curve 2, and the voltage across the capacitor by Curve 1. Neglecting losses, a capacitor consumes no real power, just the reactive power required to maintain the electric field between the plates. This reactive power is also +90º out of phase with real power. The impedance of a capacitor is called *capacitive reactance*. The resistive (real power) component of its impedance is usually very low, and typically neglected in most power system calculations.

An **inductor** is a device consisting of conducting materials, such that when AC voltage is impressed on it, the current flowing in it is –90º out of phase with the voltage . In Figure 1, the current in an inductor could be conceptually represented by Curve 1, and the voltage across the inductor by Curve 2. An inductor has *inductive reactance*, and the reactive power it consumes is also –90º out of phase with real power.

Most major components of the transmission system, including generators, transmission lines, transformers and motor loads, are basically inductive devices, whose inductive impedance is usually an order of magnitude larger than their resistance. However, by virtue of being conductors separated by an insulator (air) from a conducting plane (the ground), transmission lines also have a certain amount of capacitive reactance, which is normally overshadowed by its inductive reactance. When a transmission line is lightly loaded and not consuming a lot of inductive power, its capacitance can come into play, especially at 500 kV levels and above, causing a rise in line voltage.

When power is being transferred through a transmission line, there will be a voltage drop across the line proportional to the impedance of the line times the current. The acceptable voltage drop will be one of several important factors that limit the maximum amount of power that can be transferred.

In the AC grid, capacitive devices are used to help correct the voltage drop: when connected between the high voltage line and ground (parallel connection), they consume capacitive reactive power, which, because it is 180º out of phase with inductive reactive power, nets out an equivalent amount of it. The result is that the total power, being the algebraic sum of real and reactive power, is lower, the total current is lower, and voltage drop on the system is less. This function is called *voltage support.*

When connected in series with the transmission line, the reactance of capacitors can compensate for the reactive impedance of the line, making the line appear to have less inductance; the line appears to be electrically "shorter" to the system, increasing power transfer, reducing losses, and increasing system stability margin. Used in this way, the series capacitors are called *series compensation* of the transmission line.

Inductors as they are used in the power system are basically large coils of wire that are designed to have high values of inductive reactance. When connected between high voltage and ground, they have the opposite effect of capacitors, i.e., they reduce the voltage. This is useful during periods of light loads when the system voltage tends to rise. When connected as an impedance device in the neutral of substation transformers, they can mitigate the effects of fault currents and circulating ground currents in substations.

Loads

Any customer device or equipment that consumes electric energy is called a load. Lights, motors, appliances, and electronic devices are all types of loads. For the transmission system, loads are usually aggregated at a very high level, such that a MW of load can include many customers and many types of equipment. Loads can have both real and reactive power characteristics, and also rotating inertia (e.g., motors), which becomes an important consideration when studying the stability of the electric system.

Storage Systems

Generically, a storage system is any device that stores energy in any form and discharges it in any form. In the AC transmission system, storage systems take AC power from the grid, convert it to another form, store it, then return it to the grid as AC power. Storage can be used to shift load peaks, relieve congestion on transmission lines, provide frequency and generation regulation, provide ancillary services such as black start and spinning reserve, enable "firming" of renewables capacity for market transactions, and mitigate the fast ramping and intermittency of renewables plants. The major types of storage that are, or could be, used in the electric grid include:

Hydro plants: store the potential energy in water, and discharge it as electricity. (A pumped hydro plant has an upper and a lower reservoir; it uses electric energy from the grid to pump water from a lower reservoir to an upper reservoir, then run the water back through a hydro turbine to generate electric energy.) Issues: Relatively inexpensive power, but very site-dependent, and most of the best sites are already developed.

Batteries: AC power from the grid is converted to DC power and then into chemical energy in the electrolyte of batteries, and discharged back as AC when needed. Issues: size and cost for the electric grid; general maintenance and life expectancy issues.

Flow Batteries: Basically a fuel cell with an external electrolyte tank. Electrically, it acts just like a large battery storage system.

Flywheels: AC power from the grid is converted to DC power and then into rotating energy in the flywheel, and discharged back as AC when needed. Issues: still in the developmental and R&D stages; cost and maintenance are general issues.

Compressed air energy storage (CAES): AC power from the grid is used to run motors to compress air; the air is used to run turbines to produce AC power when needed. Issues: Very site-dependent, as a suitable repository for the air is needed, such as a salt cavern.

Supercapacitors: Capacitors using advanced materials and designs for higher energy storage density and performance; potentially higher reliability and life due to simplicity of construction. Issues: still relatively expensive for grid applications.

Superconducting magnetic energy storage (SMES): Magnetic coils using superconducting materials to store electric energy in the form of electric current, the only form of storage to do so. With zero impedance (no resistance or reactance) in the superconducting state, SMES is potentially one of the most efficient storage media. The main issues with SMES are cost, which has increased considerably in recent years, and the need for further demonstration and development for grid-scale applications. (Some small-scale distribution applications have been successfully demonstrated.)

Issues in Getting Power from Point A to Point B

Interconnection to the Grid

The first task for any new generator, whether renewable or otherwise, is to acquire a connection to the grid. A power purchase agreement (PPA) must first be obtained from the utility to which interconnection is sought and who will accept the power produced. The power producer must then apply for a queue position with the California Independent System Operator (CAISO; the CAISO evaluates the proposed new project in view of the available capacity of the transmission network, and if found to be adequate, will approve the interconnection.

The interconnection must then be made according to the utility's requirements and standards. This will include the appropriate metering, instrumentation, protection and other equipment installed at the point of interconnection with the grid, as necessary to provide proper operation, assure the safety of the public and utility personnel, and maintain system reliability.

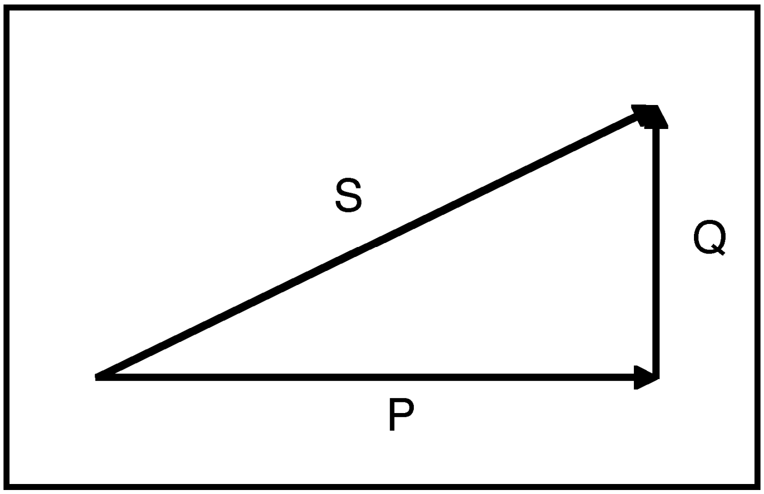
If the new generator is located remote from existing transmission lines, then a new line must be built from the generator to an interconnection point with the grid. Traditionally, vertically-integrated utilities planned the new transmission along with the generation they built. After industry restructuring, independent generators would try to locate as close to existing transmission as practical, because new lines dedicated to new generation had to be paid for by the new generation. For new renewables plants needing new transmission, this poses a significant cost barrier. California has proposed a new tariff arrangement to facilitate the construction of transmission lines to renewable resource rich areas. With this tariff, a plant will only pay a pro rata share of the cost of the line as a proportion of the full capacity of the line. Additional plants added at another time will then also pay their proportional share.

Voltage and Power Factor

Power factor is a measure of how much real power a generator is producing, or a load is consuming, compared to the total (complex) power. It is denoted by a number between 0 and 1.0. A power factor of 1.0 means the real power is equal to the total power (i.e., there is no reactive power). An example would be a resistive heating load. For loads consuming reactive power, such as motors, the real power will be less than the total power, and the power factor will be less than 1.0, and either "leading" or "lagging." "Leading" power factor denotes capacitive reactive power, and "lagging" power factor denotes inductive reactive power.

Figure 3 graphically depicts the relationship between real and reactive power, and the total power: the total (complex) power is the algebraic sum of the real and reactive power: $S^2 = P^2 + Q^2$. The power factor is defined as the ratio of real power to the total power. For example, if the total power is 5 MVA, and the real power is 4 MW, the power factor is 4/5 = 0.8.

Figure 4. Relationship Between Power (P), Reactive Power (Q) and Total Power (S)



System operators strive to keep reactive generation and reactive load in balance, just as they do with real power generation and loads. If there is not enough reactive generation to balance with loads, system voltage will fall below acceptable operating limits, leading to voltage instability and possible system collapse.

Thermal Limits

When current flows through an element of the power system, such as a transmission line or transformer, heat is created from the internal resistance of the element. The thermal limit of the element is defined as the maximum current (or power) the element can carry before reaching its limiting (safe) design temperature. For example, a transmission line conductor constructed of all-aluminum strands typically has a safe operating temperature of 75°C, above which it is assumed the aluminum strands will be annealed, i.e., the heat will cause loss of tensile strength and elongation of the strands, the line will sag too low and eventually must be de-rated or replaced. As another example, transformers have a limiting temperature of the insulating oil, measured at the top of the tank, that is defined as a certain number of degrees rise over ambient; this temperature derives from design specifications to ensure the transformer core does not exceed a temperature at which internal damage, such as insulation breakdown or internal arcing, might occur.

Power Quality

Quality power does not have a standard definition, but can be considered the degree to which electrical quantities in the power system are constant 60 Hz sine waves. Anything that affects the magnitude, frequency or smoothness of the sine wave is said to degrade power quality. Voltage dips or surges, current spikes, switching transients, intermittent load or generation, lightning strikes, poor grounding or neutral connections, frequencies other than 60 Hz (harmonics), radio frequency interference (RFI) from corona discharge, static, etc., are all examples of phenomena that can affect the power line signal. Poor power quality can affect loads, especially electronic loads and sensitive customer processes. Standards for power quality are currently being developed by the IEEE Standards Society.

(Other) Physical Limits

Circuit Breakers

Circuit breakers are large switches that act to interrupt the flow of current when a fault occurs on the system, to protect expensive equipment such as generators and transformers from overload and possible damage. Breakers must open internal mechanical contacts and extinguish the arc of current that forms between the contacts. The power flow on the system cannot exceed a level such that the circuit breakers are unable to handle the fault currents that may occur. Fault currents are approaching, and in some cases exceeding, the capabilities of circuit breakers available today; this is causing utilities to split buses, use neutral reactors in substations, or other measures that limit electric system capacity, reliability and flexibility.

Splices

Transmission line conductors sometimes break, and splices are frequently used to connect the broken ends back together. Splices can be a weak point in the line, both mechanically and electrically, and can limit how much current (and power) can flow in the line.

Insulation

All high-voltage parts of the electric system must be insulated from ground and from each other. The quality and quantity of insulating materials employed in a given situation is a direct function of the voltage level. Overhead transmission lines use ceramic or fiberglass/polymer suspension insulators to keep the conductors from the steel tower and the ground. Underground cables and transformers must use layers of oil-impregnated paper or high-density polyethylene between the copper conductors and the conduit or tank, respectively. Post insulators are used extensively in substations to support and isolate busbars, switches and other equipment from the ground. Insulation breakdown can occur due to excessive current flow, transient overvoltages, lightning or switching surges, degradation from the environment, or other causes.

Stability Limits

In the normal (steady) state, all generating machines on the power system are producing constant 60 Hz voltages and currents. This condition is called **synchronism**, in that all generating machines are synchronized with the grid at 60 Hz. The **stability** of the electric power system is basically defined as the ability of all generating machines to remain in synchronism with the grid in an equilibrium state with currents, voltages and power flows all within acceptable limits; moreover, if system imbalances or disturbances occur, the system must be able to return to an equilibrium state.

Stability analysis is divided into the following subsets of overall system stability:

Transient Stability

Transient stability is defined as the ability of the electric system to remain in synchronism (i.e., return to a synchronous equilibrium state) when a fault or other system disturbance occurs. Examples of faults are short circuits, such as a transmission line conductor touching a tree, the ground, or another line; or sudden loss of a key system component such as a transformer or a generating unit. During a fault, which typically has a duration of a small fraction of a second, the input power to a generator remains steady, because of the high inertia of the prime mover, while the electrical power output is reduced or interrupted because of reduced voltages during the fault; the excess power has nowhere to go except into speeding up the rotation of the machines. (Analogy: keeping your foot on the accelerator while pushing in the clutch.) If the total accelerating energy is large enough, the machine will speed up to the point where it loses synchronism with the grid, and protective relays will trip it off the system, making the fault condition worse. Also, faults sometimes result in transmission lines or other system components being removed from service by protection systems, which can cause system voltages to drop. If voltage oscillations are too large, relays set to detect undervoltages will act to drop load to prevent system collapse.

Transmission planners carefully study the most likely system contingencies and make sure that protection systems, including special protection schemes (SPSs) and remedial action schemes (RASs), are designed and coordinated such that the system remains stable for those contingencies. Transient stability analysis tools model the fast dynamics of electric generators to evaluate whether the system can remain stable in the 0 – 30 second time frame.

An important factor in the stability of a rotating machine is its inertia: the total angular momentum of its turbine-generator assembly. As generators respond to a transient fault, machines with high inertia (large rotating mass) will generally accelerate more slowly than lighter machines, and oscillate at a lower frequency as they settle into a new equilibrium state. As long as the oscillations die out, and generators return to an equilibrium state, the system is said to be stable for that contingency. An unresolved issue with high penetration of renewables plants is the impact of lower total rotating inertia in the system, as thermal plants are displaced or retired; it is not clear whether overall system stability will be better or worse, and further study of this issue is needed.

Synchronous generators have control systems (excitations systems and power system stabilizers, or PSS) that are calibrated to provide the best transient response to disturbances; experience has shown that mis-tuning of these systems, or incorrect modeling parameters in analysis tools, can negatively impact transient stability of the grid very significantly.

Even if the system remains stable after a disturbance, voltages, currents and power flows will oscillate (increase and decrease in magnitude) before settling down to an equilibrium state. The rate at which this settling down occurs is a measure of system **damping**: the more quickly the system settles down, the higher the damping. Damping is a combination of the aggregate resistances in the system, as well as the active control systems such as generator excitation systems and PSSs. Sustained or prolonged oscillations are an indication that the operating state is close to instability due to poor damping.

Dynamic Stability

Dynamic stability is the ability of the power system to remain in or settle into an equilibrium state when there is an imbalance between overall generation and load. If there is more load than generation, the generators on the system will start to slow down, voltage and frequency will drop, and if not corrected, this situation will lead to system collapse. If generation exceeds load, generators will overspeed and be tripped off by protective relays, leading to disturbances and possibly outages. The system operator monitors this situation, and procures ancillary services that provide generator regulation in response to the ever-changing loads on a short-term basis. Dynamic stability analysis programs model the slower dynamics of generators, such as turbine governor controls and the slower parameters of excitation systems, to analyze dynamic stability over the zero-to-several minutes (up to maybe 30 minutes) time frame. As with transient stability analysis, mis-tuned systems and poor dynamic models can contribute to dynamic instability.

Another manifestation of dynamic instability that has appeared in the Western grid recently is the phenomenon of sustained low-frequency (or low-level) oscillations. These are usually in the 0.5–3.0 Hz range, and can occur with no apparent triggering cause; their origins are not well known, but could arise from a complex set of interactions between generators. At the present time, dynamic stability modeling programs have not been successful in modeling low-frequency oscillation phenomena.

Voltage Stability

Voltage stability is a special case of dynamic stability; it is the ability to maintain adequate voltage levels throughout the system and avoid system problems due to lack of voltage support. Key to this ability is adequate reactive power reserves. If the reserve margin is too small, system voltages could deteriorate and eventually lead to voltage collapse. Voltage security analysis (VSA) programs are designed to evaluate the voltage margins and reserves in the system to ensure reliable operating margins considering the voltage requirements of the system.

Frequency Stability

Frequency stability is the ability of the electric system to maintain a steady 60 Hz frequency under changing generator and loading conditions. Frequency regulation, as it is called, is an ancillary service procured by the system operator from generators in the market, or provided by generators directly controlled by the system operator, in which generators vary their output to counteract changes in frequency. On a system level, the system operator must monitor the area control error (ACE), which is the accumulated (frequency-deviation)*time occurrences, and dispatch generators to bring this quantity to zero over the longer term (15 minutes or so). Utilities are required by FERC/NERC to maintain zero ACE to keep imbalances in one utility from affecting neighboring utilities' systems.