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Program on Technology Innovation: Scenario-Based Technology R&D Strategy for the Electric Power Industry: Final Report

Volume 2 - Background Information and Details

Technical Report

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REPORT SUMMARY

To help address the many challenges facing the electric power industry in the next 20 years, an effective process of technology R&D planning is needed. Based on input from a broad range of stakeholders and using a proven scenario planning process, this report presents a comprehensive technology R&D strategy for the next two decades that spans the breadth and depth of challenges and opportunities facing the North American electric utility industry.

Background

Over the last several years, EPRI led a broad-based industry endeavor to develop the *Electricity Technology Roadmap*, a high-level document that provides guidance on strategic technology planning over the next 40-50 years for the electricity industry. However, significant uncertainties over this timeframe – such as fuel prices, the economy, the environment, technology advances, and regulatory policies – complicate effective identification and development of R&D priorities. To address these uncertainties and to develop a nearer-term technology-oriented action plan, EPRI undertook an *Electric Power Industry Technology Scenarios* project that uses scenario planning to explicitly incorporate the above uncertainties and focuses on a 20-year planning horizon. The first deliverable in this project, published in December 2005, defined four carefully specified future "what if" scenarios that were used as the basis to prepare this report.

Objectives

To describe the critical technology R&D needs of the electric power industry and map them to the four scenarios defined in earlier EPRI work.

Approach

To obtain initial input on technology R&D needs, EPRI held a series of workshops with stakeholders from EPRI, utilities, and other organizations. The workshops originally identified 14 subject areas of R&D needs. Subsequent analysis of the information gathered and insights gained from a series of interviews with subject matter experts at EPRI expanded this list to 20 subject areas. The results of the original workshops and the follow-on EPRI staff interviews were used to identity critical R&D needs and to map them to the scenarios. This information was then used to develop this report. Subsequently, the EPRI Research Advisory Council (RAC) performed a priority rating of the top R&D projects, which was also used to develop this report.

Results

This report describes the technology R&D needs that are particularly important in the following seven areas: power generation, electric energy storage, environment, power delivery, end uses of electricity, power and fuel markets, and technology innovation/emerging technologies (e.g., biotechnology, nanotechnology, smart materials and sensors, and advanced information

technology). Volume 1 of this report provides an executive overview encompassing the key R&D needs, their timelines, and key conclusions and recommendations. Volume 2 provides important background material and details of the key 20 R&D needs, including the relevant mapping of each R&D need to one or more of the "what-if" scenarios.

EPRI Perspective

This report acts as a crucial bridge between the 3-5 year planning that some entities in the electric power industry are conducting (e.g., EPRI's 3-year strategic plan) and the longer-term (40-50 year) forecasts in the previous *Roadmap* efforts. Audiences for this report include internal decision makers at EPRI, electric utilities, government agencies, and other stakeholders. EPRI personnel will be able to use this report in the near term because many of the identified technology R&D needs require timely near-term EPRI actions. Opportunities also exist to use this report as a framework to set R&D milestone goals. Utilities can use this report to develop/refine individual utility technology R&D strategies and plans. Also, as appropriate, government agencies, regulators, consumer groups, equipment manufacturers, and others can use this report to help guide their strategic plans and activities.

EPRI plans to update the report periodically, as needed to reflect new technological advances, regulatory realities, market changes, and economic factors facing the electric power industry. Additional recommended work includes developing a plan to prepare for, and react effectively to, scenario "wild cards" – additional institutional, political, financial, technical, or social changes not explicitly addressed in this report – that could have a major impact on electric power industry R&D. Future work should also address an R&D strategy for the critical areas of human resources in the electric power industry; review and compare the findings of this document with the findings of roadmaps and visionary documents developed by other organizations in the electric power industry; and develop estimated costs, roles, and responsibilities of key stakeholders in each key R&D area.

EPRI is also offering interested utilities the opportunity to apply this technology R&D planning process to their particular challenges, which can include competitiveness, optimal use of limited investment capital, human resource and management development, and merger and acquisition opportunities. Related EPRI reports include 1013016 (2005), 1011001 (2004), 1009321 (2003), and 1010929 (2003).

Keywords

Technology R&D planning
Electric power industry
Scenario planning
Electricity Technology Roadmap
Strategic planning
Utility R&D planning

ABSTRACT

In the last several years, EPRI has led a broad-based industry endeavor to develop and publish the *Electricity Technology Roadmap*, a high-level document that provides guidance on strategic technology planning over the next 40-50 years for the electricity industry. However, critical uncertainties over this timeframe – such as fuel prices, the economy, the environment, technology advances, and regulatory policies – complicate effective identification and development of R&D priorities. To address these uncertainties and to develop a nearer-term technology-oriented action plan, EPRI undertook an *Electric Power Industry Technology Scenarios* project that uses scenario planning to explicitly incorporate uncertainty and focuses on a 20-year planning horizon. The first deliverable in this project, published in December 2005, defined four carefully specified future scenarios. The purpose of the present report is to describe the critical technology R&D needs of the electric power industry and map them to the four scenarios defined in the December 2005 EPRI work. This report is not intended to include an exhaustive list of technology R&D priorities; instead, it covers R&D needs perceived to be particularly important. The report also presents preliminary technology R&D timelines that address the most critical R&D needs. To obtain initial input to develop the technology needs, EPRI conducted a series of workshops with stakeholders from EPRI, utilities, and other organizations.

Audiences for this report include both EPRI internal R&D decision makers, as well as electric power industry R&D decision makers. EPRI personnel will be able to use the information in this report in the near term because many of the technology R&D needs identified herein require timely action. Hence, the R&D topics identified can be used to inform EPRI's short-term (3-5 year) planning processes that are annually updated. Opportunities also exist to use the recommendations in this report as a framework to set R&D milestone goals. Utilities can use the framework and content of this work to develop/refine individual utility technology R&D strategies and plans. Also, as appropriate, government agencies, regulators, associations, consumer groups, equipment manufacturers, and other stakeholders can use this report as input to help guide their strategic plans and activities. EPRI plans to update the report periodically, as needed to reflect new technological advances, regulatory realities, and economic factors facing the electric power industry.

The executive summary report (Volume 1) provides an overview of the project, recommended timelines for key R&D needs, as well as key conclusions and recommendations. Volume 2 of this report contains background information and detailed information on the R&D needs in each of the identified 20 technology areas.

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INTRODUCTION

Background

In the last several years, EPRI has led a broad-based industry endeavor to develop and publish the *Electricity Technology Roadmap*,[1] a high-level document that provides guidance on strategic technology planning for the electricity industry. The *Roadmap* describes a global vision for electricity in the 21st century, a plan to set strategic technological priorities, and an outline of the associated technologies needed to achieve the vision. The *Roadmap*'s goal is to encourage the debate, leadership, innovation, and investment that will enable electricity to realize its potential for improving economic productivity, protecting the environment, and increasing the quality of life.

The time horizon of the *Roadmap* extended to 2050. A fundamental premise of this work is the feasibility of painting a vivid picture of the desired electrified world in 2050, and the ability to reach this end state through a combination of decades-long technology development efforts. During the development of the *Roadmap*, it was understood that quantitative assessments and functional specifications for such a distant future are problematic. Uncertainties in driving factors – such as fuel prices, the economy, the environment, technology advances, and regulatory policies – are large on the time scale of the *Roadmap* and do not provide sufficient granularity for R&D actions to be implemented in the next 10-20 years.

To address the uncertainties cited above and to develop a nearer term technology-oriented action plan, EPRI undertook in 2005 an *Electric Power Industry Technology Scenarios* project. It involves two major thrusts:

- Focus the principal planning effort on the time horizon of 20 years, instead of the 50-year horizon of the current *Roadmap* planning effort.
- Use scenario planning as a tool for explicitly incorporating the uncertainty inherent in the technology R&D planning process.

The first deliverable in the *Electric Power Industry Technology Scenarios* project, published in December 2005,[2] defined four carefully specified future scenarios. These scenarios provide the foundation for the present report.

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[1] Electricity Technology Roadmap, 2003 Summary and Synthesis, 1010929, 2003.
[2] Electric Power Research Institute, Electric Power Industry Technology Scenarios: Preliminary Results, 1013016, 2005

Description of Scenario Planning

The formidable challenges facing electric utility planners and executives, and other electricity industry stakeholders include envisioning how future uncertainties will affect individual technology strategies and related business plans. This includes how to address operational uncertainties and prepare the strategic responses needed for success. One way to meet these challenges is to create a set of future "what if" scenarios that assume a particular forecasted potential future actually occurs, and then develop R&D technology project plans for each "what-if" outcome. Envisioning the future, developing strategic responses, comparing responses across scenarios, and building a robust strategy help prepare for an uncertain future by developing the best set of strategic R&D plans for success.

Scenario analysis begins by developing a set of alternate futures about how the electric utility business environment might develop. The scenarios are not predictions *per se*, but credible, what-if futures. The scenarios offer plausible outcomes to existing uncertainties in areas such as fuel prices, technology improvements, market acceptance of innovation, load growth, and future environmental regulations. Each scenario should pose for decision makers the questions: "If we found ourselves in this world, what areas of our business would be most affected? How would we respond?"

Scenarios can serve the role of helping to generate ideas and options in response to changing business conditions. They stretch thinking, generate inquiry and learning, and provide a sense for areas in which innovation is needed.

The scenarios that were defined (see Section 2) are not global societal scenarios that address all global issues and all business sectors, but instead focus on the use of key drivers relevant to the electricity sector in the western world. EPRI elected to develop its own scenarios, rather than use scenarios of others, to provide a unique perspective on how technology advances can challenge the conventional wisdom of the energy future.

Purpose of This Report

The purpose of this report is to describe the critical technology R&D needs of the electric power industry, and map them to the four defined scenarios. This report is not intended to include an exhaustive list of technology R&D topics or to list a final set of R&D priorities; instead, it covers R&D needs perceived to be particularly important (whether or not EPRI now has or may have a role in addressing them), based on the critical uncertainties facing the U.S. electric utility industry today.

This report addresses institutional, political, regulatory, and financial factors to the extent that they are relevant to the defined scenarios. While this report focuses on the R&D technology needs in each of the scenarios, institutional and other factors are often inextricably linked with technology advances. Hence, institutional and other factors are also discussed in this report, but to a limited extent.

While past *Electricity Technology Roadmap* efforts and reports have adopted a long-term view (50 years), this report adopts more of a mid-term view (up to 20 years). Hence, this report is intended to act as a bridge between a) the 3-5 year planning that some entities in the electric power industry are conducting (e.g., EPRI's 3-year strategic plans) and b) the longer term previous *Roadmap* effort.

Approach

To obtain initial input on technology R&D needs, a series of workshops were held with the participation of stakeholders from EPRI, utilities, and other organizations. These workshops originally identified 14 subject areas of R&D needs. Subsequent analysis of the information gathered and a series of interviews with subject matter experts at EPRI expanded this list to 20 subject areas. Both the original workshops and the follow-on meetings at EPRI surfaced information needed to identity critical R&D needs and mapped them to the scenarios. This information was then synthesized and documented in this report.

Application of the Information in This Report

Audiences for this report include internal decision makers at EPRI, electric utility research staff and managers addressing electric utility needs, utility R&D decision makers, and government R&D decision makers.

EPRI and electric utility decision makers will be able to make use of the information in this report in the near term because many of the technology R&D needs identified herein require timely action. Utilities and other organizations will also be able to utilize and leverage the information in this report. For example, utilities can use the framework and content of this report to develop or refine individual utility technology R&D plans. Utility organizations, government agencies, regulators, associations, consumer groups, equipment manufacturers, and other stakeholders can also use this report as input to help guide, develop and/or refine their strategic plans and activities.

As part of the scenario analysis process, EPRI augmented its "what if" scenarios by identifying a broad range of potential discrete events that could have a significant impact on the electric power industry. These "wild cards" are not explicitly discussed in this report, but are listed in Appendix B to indicate the range of occurrences that are possible, some of which may have a positive or negative impact on the electric utility industry. While beyond the scope of this report, the existence of these wild cards calls for plans to enable preparation for, and reaction to, these "what if" events as well.

To provide timely value to its members, EPRI plans to update this report periodically, as needed to reflect new technological advances, regulatory realities, market changes, and economic factors facing the electric power industry.

Using Roadmap Results in Individual Company Planning

Individual companies and organizations that support the electric utility industry have concerns that mirror those of the industry, as well as concerns that are more specific to their company or organization. Also, there are micro-level or utility specific concerns that address issues such as competitiveness, optimal use of limited investment capital, human resource and management development, and merger and acquisition opportunities. The scenarios and technology implications contained in this report can be useful input into utility company analyses that address these issues. Several processes may help support these company analyses, including the following:

- If a company has developed its own set of scenarios, then the scenarios in this report can serve as a point of comparison to determine if any key factors or considerations were inconsistent or overlooked. Additionally, if a company has developed its own technology roadmap, the technology R&D needs in this report can serve as a check and point of comparison (as well as a resource for information).
- A company can determine its set of market or customer service segments to test against the scenarios presented herein. For example, a company might view the organization of its distribution or generation activities in a particular way and thus test those organizations using the scenarios to examine how market and industry conditions might alter demands on those organizations.
- Companies can use the scenarios and technology R&D needs in this report to analyze market entry strategies, especially in new markets that may emerge as one or more technologies are commercialized. Some companies may decide to consider early commitments to new technologies, while others may decide to be prompt or measured followers of a specific technology development process. As these decisions are made, the organizational and human resource requirements for such actions can be considered as well.
- Each scenario presents a different context in which to test the success of a company's current strategy, and competitive actions. Emerging merger and acquisition targets might also be identified by assessing industry dynamics or the fortunes of individual companies over the long term.

Organization of This Report

Section 2 of this report defines the "what if" scenarios used to identify R&D technology areas. The balance of this report describes the technology R&D needs in each of 20 subject areas within the electric power industry. These 20 subject areas are grouped in the following seven areas: power generation (Section 3), electric energy storage (Section 4), environment (Section 5), power delivery (Section 6), end uses of electricity (Section 7), power and fuel markets (Section 8), and technology innovation/emerging technologies (Section 9). The latter section describes innovative technology areas (e.g., biotechnology, nanotechnology, smart materials and sensors and advanced information technology), many of which could have a profound impact on electric utility assets, maintenance, and operations in the future. Section 10 documents the results of a process to perform a priority rating of the top R&D projects, performed by EPRI's Research Advisory Council (RAC).

The technology R&D needs in each of the 20 subject areas are described in approximately ten pages each. After a brief overview of the subject area, key challenges and corresponding R&D needs are described. Each of these 20 subsections concludes with a discussion of the relevant mapping of these R&D needs to the scenarios and indicates which R&D needs cut across one or more of the scenarios.

Appendix A, for the reader's convenience, delineates a composite, summary listing of all key critical R&D topics that are identified in each of the 20 subject area subsections of the report. Appendix B lists wild cards and institutional challenges that may also affect the electric power industry. Detailed analysis of these wild cards is beyond the scope of this document, but these items are worthy of attention in a future, separate study. Appendix C presents a list of acronyms used in this report, and Appendix D contains a bibliography.

In the form of an executive summary, volume 1 of this report provides an overview of this project, R&D timelines that address the most critical needs, and key conclusions and recommendations.

Roadmap Destinations and the 20 R&D Subject Areas

The *Roadmap* report identified five "destinations:"

- Strengthening the power delivery infrastructure
- Enabling the digital society
- Boosting economic productivity and prosperity
- Resolving the energy/environment conflict
- Addressing the human resource challenge

The first destination addresses the need to enhance and expand the aging power delivery infrastructure in North America – much of which was designed and built 40-50 years ago. The second destination addresses the need to ensure high reliability, quality, and security of power delivery to an increasingly sensitive set of consumer loads that reflect the digitization of society. The third destination reflects continuation of the correlation between economic growth/productivity and the increased use of electricity. The fourth destination reflects the need to effectively balance the needs for reliable electricity at reasonable cost with the need to protect the environment and human health. The fifth destination involves the growing set of human resource needs, including transferring the knowledge and experience of an aging workforce of experienced industry professionals to a new generation of power system operators, power plant designers, asset managers, and others.[3]

[3] Note that this fifth destination is substituted for the destination called "managing the global sustainability challenge" in EPRI's 2003 *Roadmap* report (Number 1010929) due to the focus on domestic challenges in the present report.

This report identifies 20 technology subject areas for R&D (see Table 1-1), which are presented and cross referenced to the five roadmap destinations above. For more information on the destinations, refer to the EPRI report, "*Electricity Technology Roadmap*, 2003 Summary and Synthesis," EPRI Report Number1010929.

The details of each of the 20 technology subject areas are presented below after a brief discussion of the scenarios in Section 2.

Table 1-1
Meeting the R&D needs in the 20 subject areas described in this report will help reach the five *Electricity Technology Roadmap* "destinations."

	Strengthen the Power Delivery Infrastructure	Enable the Digital Society	Boost Economic Productivity and Prosperity	Resolve the Energy/ Environment Conflict	Address the Human Resource Issue
Coal power generation technologies			X	X	X
Natural gas fired generation technologies			X	X	X
Existing nuclear power			X	X	X
Future nuclear power			X	X	X
Renewable resources			X	X	X
Distributed energy resources	X	X	X	X	X
Electric energy storage	X	X	X	X	X
Carbon capture, transport, and sequestration				X	X
Emissions reduction and control				X	X
Environmental science and technology				X	X
Transmission and substations	X	X	X		X
Grid operations and resources planning	X		X		X
Distribution system	X	X	X		X
Power quality	X	X	X		X
Physical and cyber security	X	X	X		X
Energy service portal	X	X	X		X
End-use energy efficiency			X	X	X
Electricity-based transportation	X		X	X	X
Power and fuel markets	X		X	X	
Technology innovation/emerging technologies	X	X	X	X	X

2
SUMMARY OF SCENARIOS

Background

Building scenarios involves a process of discussion, debate, and research to establish a set of key drivers or external variables that influence the industry. In developing the scenarios used in this report, over 100 variables that might influence the evolution of the U.S. electric power industry were considered. These variables were then grouped into the following overarching categories:

- The evolution of primary fuel markets
- Changes in social values regarding energy externalities (e.g., climate change)
- The direction and structure of world economic growth
- Changes in political values that influence regulations (e.g., priority of environmental issues)
- Lifestyle and value shifts influencing consumer demand for energy services
- The shape of the structure of the electric power industry (i.e., business models)
- The course of natural events related to climate change
- The course of price changes for electricity and consumer responses
- The evolution of the power industry infrastructure (decentralized or centralized)

The first two factors were identified as the most critical (and uncertain) and were used to initiate the scenario development process. The various combinations of high and low values for each of these two factors define four scenarios, as depicted by four quadrants in Figure 2-1. Names for each scenario were developed to reflect the essence of the combination of factors that they represent. Rather than predictions of the future, these scenarios simply represent four possible future outcomes.

A few underlying assumptions are common to all four of the scenarios, including the following:

- An aging and stressed transmission and distribution infrastructure
- Rising global prices for commodities such as steel, copper, and other manufacturing raw materials
- Continued monopoly structure for local distribution systems

- An aging workforce in the electric power industry presents unique challenges to the industry due to retirement of both experienced professionals and skilled craft trades, and due to the complexity of retaining and transferring knowledge and experience to new personnel
- Limited manufacturing capability in the U.S. to manufacture specialized components such as large forgings for nuclear reactors

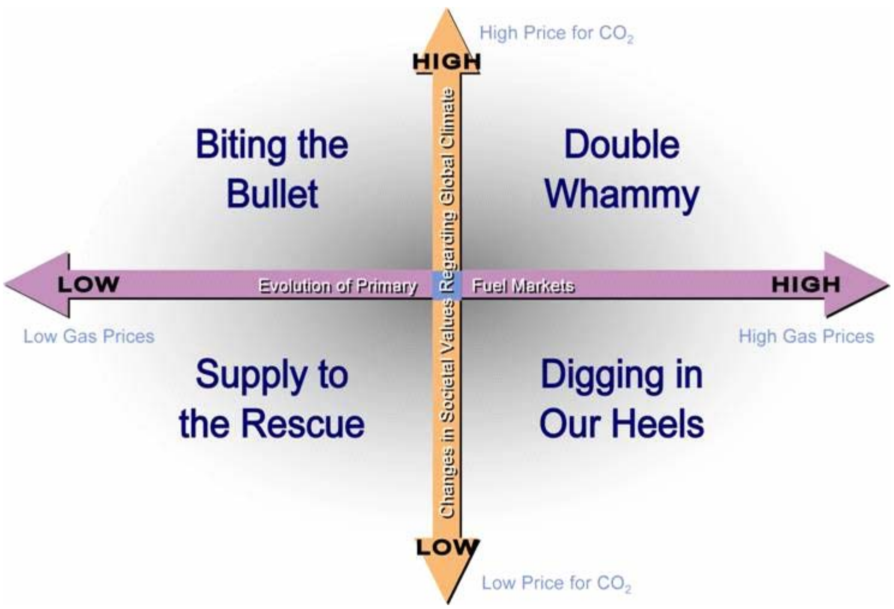

Figure 2-1
High and low values for natural gas prices and importance of environmental and other externalities (manifested in the form of CO_2 prices) define the four scenarios used in this report.

The remainder of this section describes the four scenarios in more detail.

The "Digging in Our Heels" Scenario

"Digging in our Heels" is a scenario in which change is actively resisted (see Figure 2-2). Society embarks on a "momentum strategy." The circumstances of this scenario may not be perfect, but the perceived cost of alternate strategies is deemed to be too high to receive attention.

In this scenario, natural gas and other primary fuel prices are rising, driven by growth in demand and supply constraints, but direct or imputed cost of CO_2 emissions is very low. The low cost of CO_2 derives from inconsistent political will and uncertainty regarding climate change, as well as the desire to avoid significantly burdening the energy industry with the cost of mitigating environmental externalities. This does not imply that the environment is an unimportant concern for electric utilities or consumers – just that it is not a high priority on a national level.

Figure 2-2
Overview of "Digging in Our Heels" Scenario

Moderate to fast global economic growth and changes to geopolitical circumstances around the world evolve relatively slowly, and the U.S., Europe, China, and India are world leaders. The U.S. resists some suggestions to impose high costs on its economy to address what are perceived as unclear links between human activity and climate change. Many other nations, but not all, follow the U.S. lead. China and other developing economies, though using more modern and efficient technologies to fuel growth, make no extraordinary efforts to address climate change issues.

Global leaders focus instead on wealth creation and poverty reduction. Politics and concern for jobs, more than the level of energy and electricity prices, drive global economic competition. Energy price increases do not prevent long-term economic growth. U.S. labor productivity continues to grow, but wages remain low because of competition from China and India, immigration, and reduced trade barriers in general.

Adequate energy supplies, though of some concern, are maintained because sufficient investment flows into resource development. Businesses and consumers accept increasing energy prices, even with a few shocks, since the value added in final energy consumption is high. The U.S. economy continues to shift toward a high-technology, service-oriented base with slow but steady increases in the adoption of energy-efficient technologies. Thus, U.S. consumers maintain a high and improving standard of living.

However, the electric utility industry does not keep pace with the rest of the economy. Concerns for full cost recovery and tepid consumer interest dampen electric utility industry plans to offer substantially higher-quality services, or invest in new and replacement infrastructure or advanced technologies. Central station technology dominates decisions regarding new generating capacity at the expense of distributed generation. Natural gas and coal are the fuels of choice in the near term (2005 to 2015). New nuclear generation becomes increasingly competitive for a significant portion of the generation mix in the post-2015 time period. Also, the reliability of the electric generation and delivery system does not significantly improve, and investments in the power delivery infrastructure are limited to the basic level required to meet electricity load growth, which tracks just below economic growth rates as energy intensity declines. Some conditions in parts of the U.S. currently reflect this scenario.

The "Supply to the Rescue" Scenario

In the "Supply to the Rescue" scenario (see Figure 2-3), the industry and consumers rely on supply-side solutions to a broad range of energy issues. The abundant supply of low-cost natural gas in this scenario spurs economic growth and development, particularly in energy dependent businesses. In this scenario, government and industry make large investments that lead to ample supplies of electricity and stable moderate prices for both natural gas and other primary fuels. Consumers and politicians believe that the current pace of moderate improvements in environmental quality is sufficient to meet societal goals and that technological innovation will continue to provide timely improvements. Consumers prefer continued and stable economic growth over a difficult-to-prove and/or debatable connection between energy use and climate change.

North America, Western Europe, China, and India anchor global economic growth as world trade expands and international conflicts diminish. Technological innovation in computing, communications, bio-science, nanotechnology, and other areas continues to move the U.S. toward a more knowledge-based economy with more efficient use of energy resources. The shifts in global production and distribution of goods continue to impact the nature and level of job growth in the U.S., but overall economic growth continues at a moderate pace.

Some natural gas reserves are located far from the likely point of end use in the U.S. and thus influence U.S. geopolitical and military planning. To address national security concerns, the U.S. moves ahead quickly with infrastructure development to enable the importation of more natural gas. This trend continues as more new gas and oil discoveries are brought on line. Developing and implementing liquefied natural gas (LNG) technology moves to a level of international cooperation that mirrors that in oil development and transportation.

Eventually natural gas prices fall relative to coal, and natural gas is the most competitive choice as a fuel for power generation. With low gas prices, many utilities and commercial/industrial companies install relatively inexpensive distributed generation systems that are fueled by easy access to existing and new natural gas supplies. Energy suppliers point out that displacing coal generation with natural gas for power generation reduces CO_2 emissions – a "no regrets" strategy. This scenario reflects conditions that occurred in the late 1990s in most of the U.S.

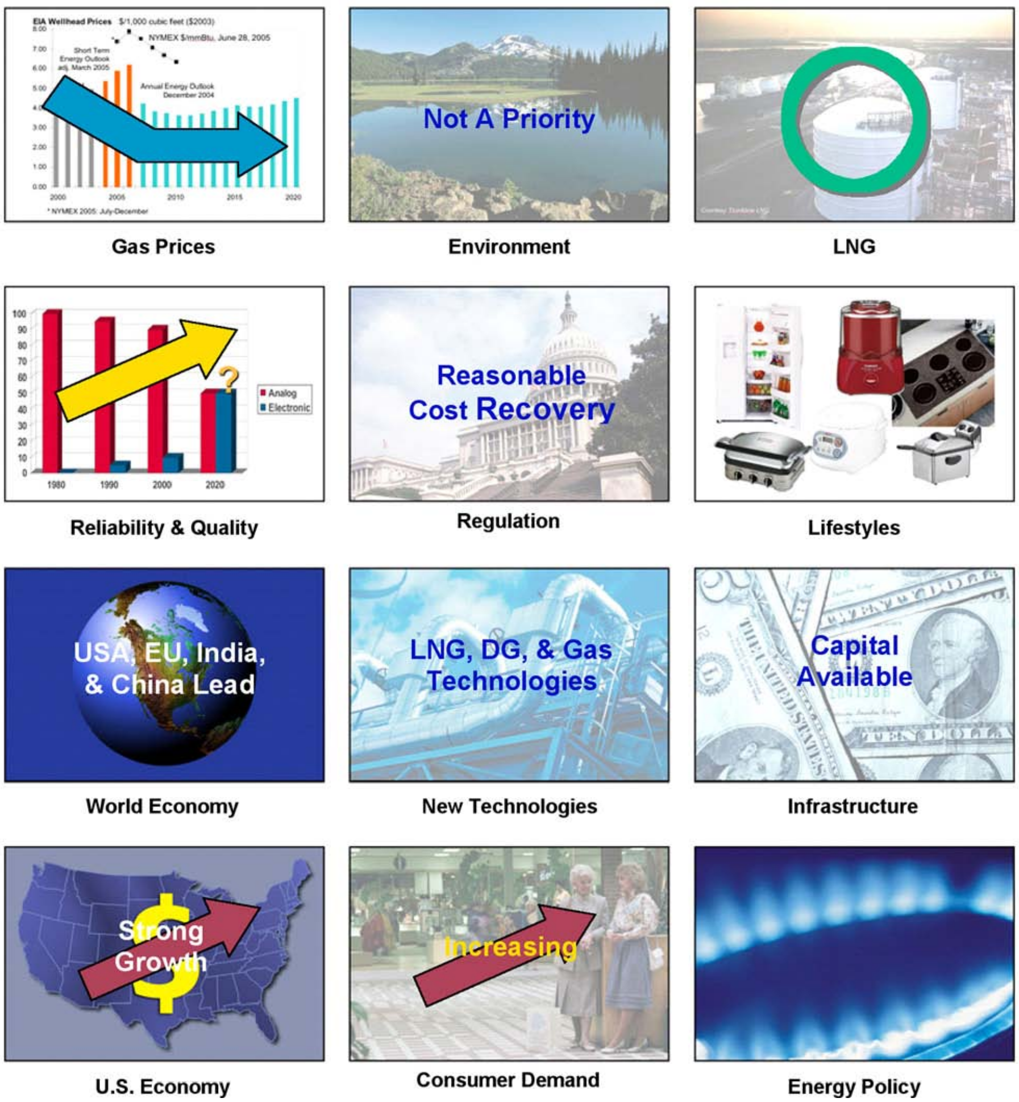

Figure 2-3
Overview of "Supply to the Rescue" Scenario

The "Double Whammy" Scenario

The "Double Whammy" scenario, as the name suggests, incorporates both high gas prices and high societal concerns about environmental costs (see Figure 2-4). Taken together, these factors produce a more than proportionate share in their impact on the economy. Technology advances offer a collaborative basis for meeting the challenges of this world.

This scenario reflects a significant change in beliefs and values of the majority of Americans, industry, and government leaders toward the position that anthropogenic changes in global climate are occurring, that they are harmful, and that they must be addressed soon. Conflicting scientific opinions persist regarding anthropogenic activities and global climate change, but the political perceptions about consequences of global climate change render the debate moot.

The U.S. joins an international consensus that is willing to accept sudden and sustained high prices for traditional energy sources. The expectation is that the resulting technology upheaval and shift in investments by government and businesses will eventually moderate energy demand and costs while sustaining the environment. As a result, businesses and consumers face increasing fuel prices due to policy or taxation and lingering demand, and these higher prices do not decrease immediately. The direct and imputed cost of CO_2 emissions grows rapidly at first, but over time increases more slowly.

This policy shift greatly accelerates investment and innovation. Business leaders see not only market potential, but are also anxious to invest in short-term and long-term technology innovations that can support global competitiveness.

Led by North America and Western Europe, a mutually supportive business atmosphere evolves between business leaders, politicians, and consumers to combine voluntary actions and market incentives to shift energy use patterns toward a cleaner and more sustainable path. The initial focus is on improved end-use efficiencies, combined heating and power, nuclear power, energy storage, and renewables. Over time, innovations occur that generate surprisingly positive impacts on efficiency, cost, and environmental quality while delivering enhanced power generation and environmental features.

In many cases, China and India are able to more easily install the best available environmental technology because they have a smaller sunk base of assets. Instead, their economic growth increases the demand for fuels.

Clean coal-based generation and nuclear energy become important elements in a transition strategy to replace fossil generation with low- or non-CO_2-emitting generation. Natural gas-fired generation is at a disadvantage because of its high cost, and the high cost of capturing CO_2 from the exhaust of a gas-fired generator. Over time, policy makers realize that renewables alone are incapable of addressing climate change, so they commit to nuclear power and coal as a major part of generation portfolios. This scenario reflects conditions that are currently reflected for example in the European Union and Japan. Also, California and New England seem to be headed in the direction of this scenario.

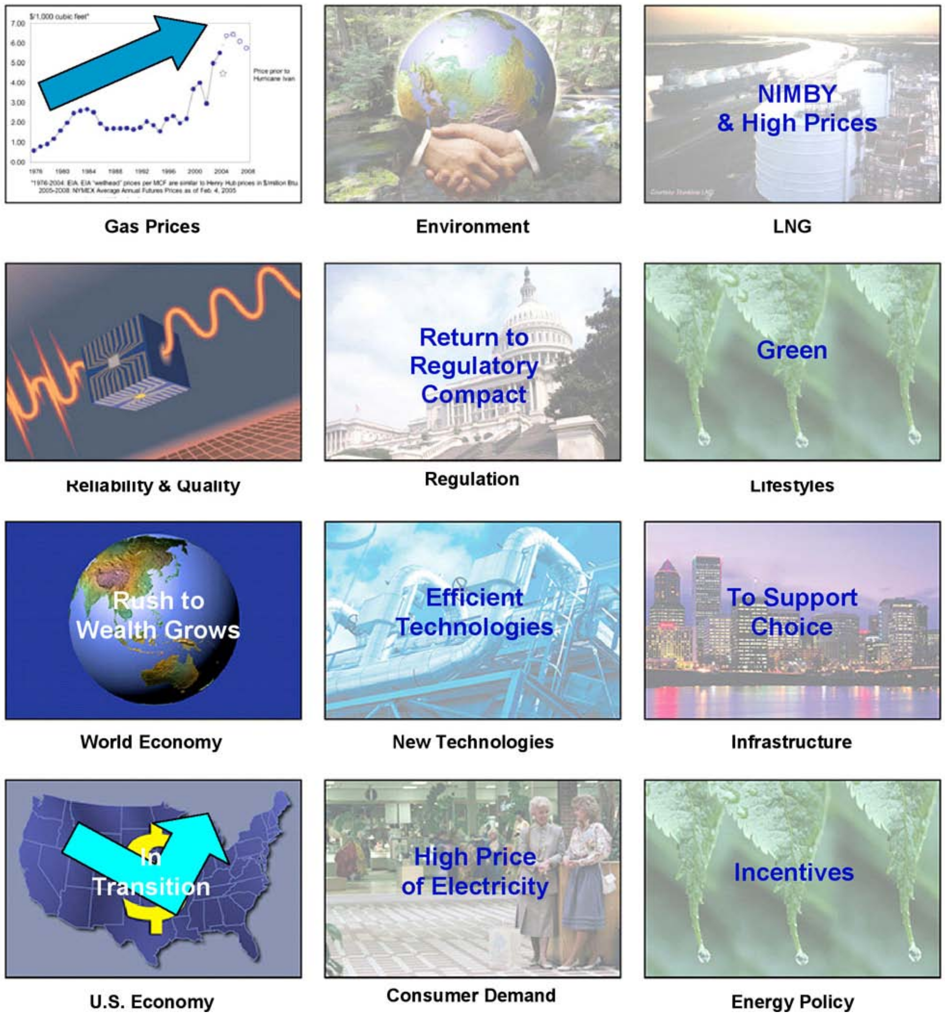

Figure 2-4
Overview of "Double Whammy" Scenario

The "Biting the Bullet" Scenario

The final scenario postulated is the "Biting the Bullet" scenario, which encompasses the need to take painful actions in the near term to forestall even more painful consequences in the future (see Figure 2-5). The climate change issues of this scenario have such a large impact on society that precipitous actions are required as society attempts to deal with a series of crises.

A series of world-scale, climate-related events and wide public acceptance of scientific thinking change worldwide views about climate change. Based on changing voter perceptions that the U.S. must join with other large economies to address climate change issues, U.S. policy makers take strong actions. They increasingly impose regulations and standards that dictate many industry choices, which leads to adverse economic outcomes in the short term. But these measures are considered to be a cost that is worth incurring to ensure longer-term benefits.

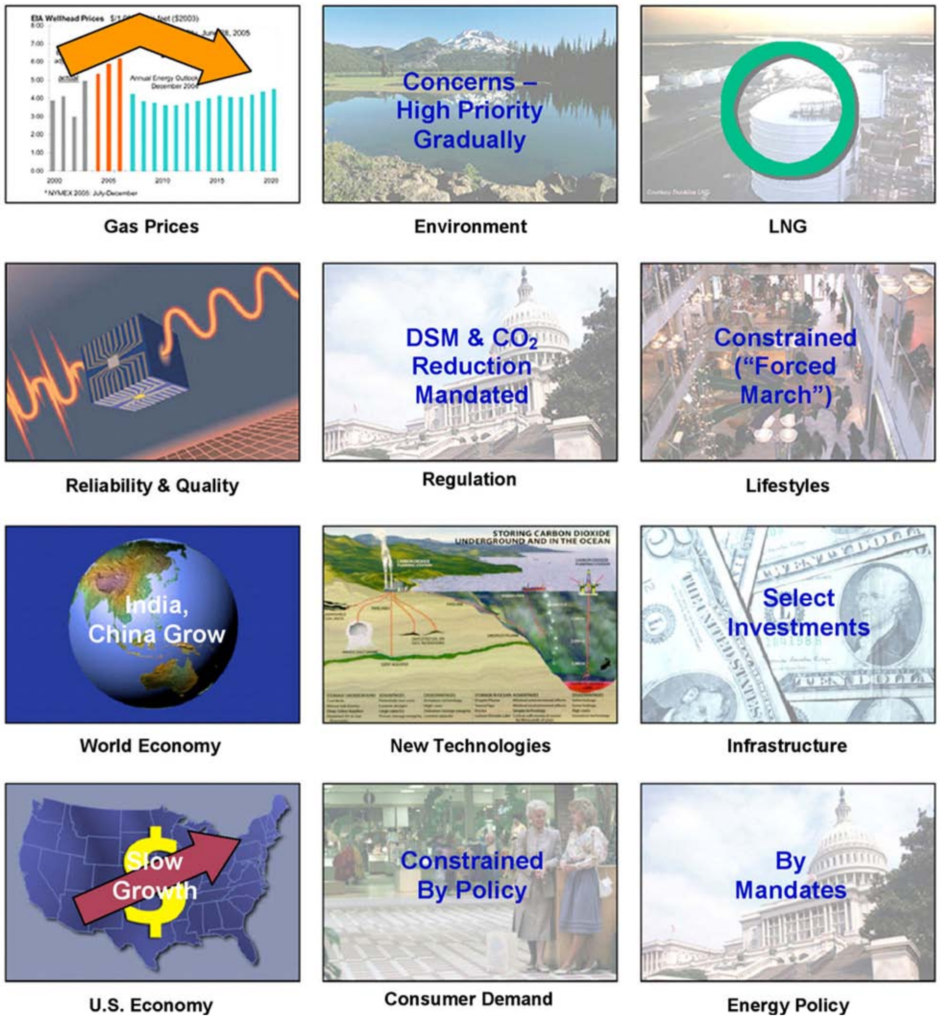

Figure 2-5
Overview of "Biting the Bullet" Scenario

The policy changes moderately reduce demand for primary fuels. With slower economic growth, fuel prices moderate and begin to decline. Industries with large sunk costs in assets that are forced out of use enter a period of restructuring, but government investment eases some of the burden.

A shift to more sustainable lifestyles is forcibly pursued and politically supported, pushing some immature technologies into the market despite uncertainties regarding lifecycle costs and long-term benefits. Industry accepts the changes because voters demand them and government promises to buy-down the risk of these investments.

The U.S. decides to accept lower economic growth and puts pressure on other developing nations, especially China, to do likewise. Along with Western Europe, the U.S. imposes trade sanctions on nations with poor environmental standards. This slows the overall rate of global economic growth, but also protects jobs and promotes new investment in domestic industries.

Consumers believe that short-term sacrifices and changes in behavior and lifestyle will pay off in the long term by reducing the likelihood of adverse climate changes and moderating primary fuel price increases. Technology innovations in digital applications, bio-science, and other fields are directed toward creating products and services that support sustainable lifestyles.

The imposition of a high CO_2 tax slows economic growth, and without low-cost carbon capture and sequestration technologies, makes all fossil fuels unattractive choices. It is assumed in this scenario that once alternative supply technologies are in place, industry and consumers are prohibited from reverting back to fossil fuels. Natural gas is allowed as a transition fuel but with quickly increasing constraints related to its greenhouse gas emissions. France, with its nuclear mandate, currently faces conditions that are closest to this scenario.

3
TECHNOLOGY R&D NEEDS: POWER GENERATION

This section covers technology R&D needs in the power generation area. It addresses the following power generation technology areas:

- Coal power generation technologies
- Natural gas fired generation technologies
- Existing nuclear power
- Future nuclear power capabilities
- Renewable resources
- Distributed energy resources

Coal Power Generation Technologies

Overview

Coal is the primary fuel for generation of electricity in the United States and many other countries. In the U.S., more than 350 GW of installed coal plant capacity generates roughly one-half of all kWhs produced. Coal is abundant in the United States, with the potential to provide hundreds of years of power. Its price is relatively low, stable, and less sensitive to international oil/gas price fluctuations. (Of course, coal combustion poses environmental impacts, which are addressed in the section on emissions reduction and control in this report.)

To accelerate commercial deployment of advanced coal power systems, EPRI and the electric utility industry are leading a broad-based collaborative program encompassing the development, demonstration, and deployment of technologies including integrated gasification combined-cycle (IGCC), ultra-supercritical pulverized coal (USC PC), and supercritical circulating fluidized-bed combustion (SC FBC). Known as CoalFleet for Tomorrow®, or simply "CoalFleet," the initiative aims to tackle the technical, economic, and institutional challenges to making clean coal power systems a prudent investment option for both the short term and the long run.

Boosting coal-based power plant efficiency to high levels yields environmental benefits throughout the process of converting primary fuel energy to electricity at the bus bar. Direct benefits include reduced energy consumption and environmental impacts from coal mining and transportation, and at the power plant itself, reduced water consumption, less waste heat rejection, fewer solid combustion products, and reduced air emissions.

In addition, increasing plant efficiency reduces plant carbon dioxide (CO_2) emissions, which are linked to global climate change. Refer to the section in this report on carbon capture, transport, and sequestration for more information.

Other direct benefits also result. Fewer coal trains means less strain on the U.S. transportation network. In some cases, equipment can be sized smaller throughout the plant. Coal piles and ash ponds, for example, can be smaller for a given number of days of storage, reducing land requirements and inventory costs. Where investments in efficiency make sense economically, they also make sense environmentally.

Integrated Gasification Combined Cycle Technology R&D

In IGCC plants, coal is not burned directly, but rather partially oxidized in a high-pressure gasifier to form a synthetic gas, also known as “syngas” (see Figure 3-1). The coal is partially oxidized in the presence of oxygen, which is derived from air in the air separation unit (ASU). Ash forms an inert (or non-leachable) slag that is removed from the gasifier for disposal or commercial use. The syngas is cooled and sulfur compounds are removed, which are converted to elemental sulfur or sulfuric acid that can also be sold commercially. The clean syngas is then combusted in a combustion turbine (CT)/generator, which generates about 60 percent of the electricity the plant produces. The waste heat is recovered and used to produce steam that drives a smaller turbine-generator in a combined-cycle configuration to produce additional electricity (the “CC power block” in the figure). By adding a shift reactor (a component in which chemical processes occur) between the gasifier and the gas clean-up stage, CO_2 can be removed in the gas cleanup stage, pressurized, and transported for storage/sequestration.

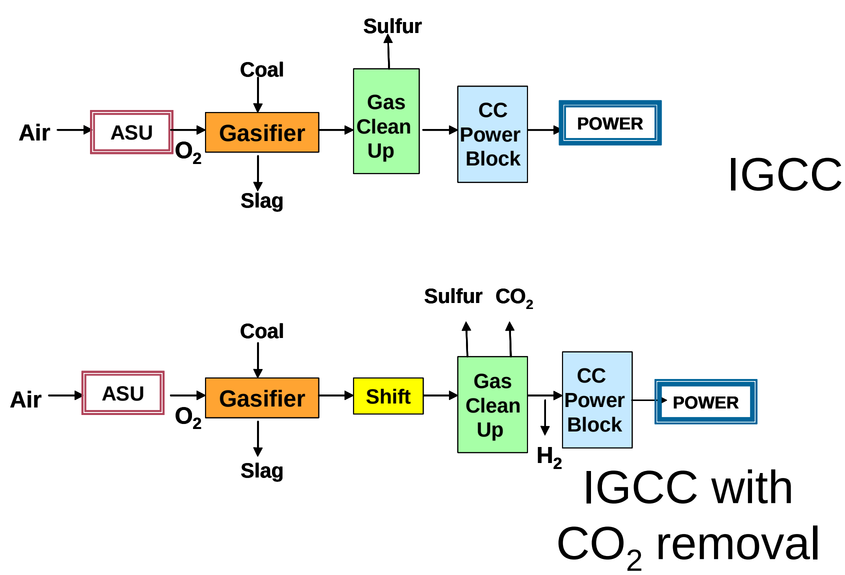

Figure 3-1
IGCC With and Without CO_2 Removal

IGCC systems combine the high efficiency, low emissions, and low water usage of CTs with the ability to run on syngas, which is coal-derived. Substantial improvement in IGCC technology has been achieved since the 100-MW "Cool Water" demonstration in the 1980s. The earlier CTs and limited design integration of that era produced a plant with a heat rate of over 11,000 Btu/kWh (31 percent efficiency, higher heating value, HHV, basis). Today, the efficiency of commercially offered IGCC plants has climbed to roughly 40 percent (without CO_2 capture) for bituminous coals because of larger, more efficient gasifiers, more efficient CTs, and advances in design integration.

However, electricity from initial IGCC plants without CO_2 capture and storage costs 15-20 percent more than electricity from conventional pulverized coal (PC) plants with state-of-the-art sulfur dioxide (SO_2), nitrogen oxides (NO_x), and particulate emission controls. IGCC's competitiveness with conventional PC plants firing bituminous coal improves if CO_2 removal is required, but such a requirement significantly reduces the power output and increases the cost of both plant types. Technology R&D needs have been identified that can significantly increase the power output, increase the efficiency, and reduce the cost of IGCC plants with CO_2 capture. Table 3-1 lists these technology R&D needs for slurry-fed gasification-based plants.

One key technology need that is shown in this table is to integrate new gasification systems with advanced CTs. This involves first assuring the reliability of suppliers' new reference designs with advanced F-class CTs and then accelerating introduction of higher efficiency G-class and H-class CTs, without compromising operating flexibility or reliability. Other key steps include using the captured CO_2 to slurry the coal in place of water, and proving a revolutionary oxygen (O_2) process called the Ion Transfer Membrane process. This will capitalize on opportunities for minimizing efficiency penalties without undue impact on operating flexibility.

This sequence of steps is expected to decrease the HHV heat rate from 11,323 to 7554 Btu/kWh. This reduction will result in an increase in HHV efficiency from 30 percent to 45 percent, while reducing the capital cost from $2016/kW to $1246/kW. At the same time, net power output is expected to increase from 454 MW to 770 MW. Slightly less dramatic, but still substantial improvements are also expected in a similar arrangement that uses dry-fed gasifiers, rather than slurry-fed gasifiers. The end result is an IGCC with CO_2 capture that is less expensive and more efficient than today's IGCC without CO_2 capture.

Table 3-1
Overview of Key Steps in Long-Term IGCC RD&D Roadmap for Slurry-fed Gasifiers

	Total $/kW	CC $/kW	Gfr $/kW	ASU $/kW	Gen $/kW	CO_2 $/kW	HHV Heat Rate	HHV Effcy	Avail - ability	SO_x lb/MMBtu	NO_x ppmvd	Mercury Removal	Net MW
Baseline plant with SCR	2016	670	661	241	271	173	11323	30.1%	90.0%	0.006	3	90.0%	454
Eliminate spare gasifier	1900	670	546	241	270	173	11323	30.1%	90.0%	0.006	3	90.0%	454
F-class to G-class CTs	1734	659	475	210	240	150	10957	31.1%	90.0%	0.006	3	90.0%	670
Improved Hg detection	1734	659	475	210	240	150	10957	31.1%	90.0%	0.006	3	>95%	670
ITM Oxygen	1623	642	463	136	234	147	10563	32.3%	90.0%	0.006	3	>95%	696
CO_2-Coal Slurry	1592	640	453	125	234	140	9929	34.4%	90.0%	0.006	3	>95%	699
G class to H class CTs	1561	629	441	122	232	137	9666	35.3%	90.0%	0.006	3	>95%	715
Ultralow dry low NO_x Combustors	1553	623	440	121	232	136	9646	35.4%	90.0%	0.006	3	>95%	716
Supercritical heat recovery steam generator	1533	623	431	119	227	133	9434	36.2%	90.0%	0.006	3	>95%	732
Membrane CO_2 Separation	1397	592	410	113	216	67	8980	38.0%	90.0%	0.006	3	>95%	770
Warm Gas Cleanup	1334	592	349	111	216	66	8801	38.8%	90.0%	0.006	3	>95%	770
H-class to fuel cell hybrid	1246	592	314	100	216	24	7554	45.2%	90.0%	0.006	3	>95%	770

Notes:
Adapted from the IEA Greenhouse Gas Programme's Report PH4-19, which was issued in May 2003,[4] the "baseline technology" uses a combined cycle with two GE 7FA CTs and selective catalytic reduction (SCR). It incorporates a two-stage water-gas shift reactor, which converts 95 percent of the carbon monoxide (CO) in the raw syngas to CO_2, as well as a Selexol acid gas removal system that captures more than 90 percent of the CO_2 in the shifted syngas. The captured CO_2 is compressed for export from the plant boundary by pipeline, but the cost of the pipeline is excluded. A GE Energy quench gasifier includes a spare gasifier train (4 x 33 percent arrangement) to feed the CTs. The amount listed for capital cost in the CO_2 capture column represents the incremental cost of the CO_2 compressors, water-gas shift reactors, acid gas removal (AGR), and the sulfur recovery unit (SRU). "CC" represents the combined cycle block, "Gfr" represents the gasification block (including coal milling, slag removal, quench, solids scrubber, low temperature gas cooling, and the AGR and SRU costs of an equivalent plant without CO_2 capture). "ASU" represents the air separation unit and associated compressors for oxygen (O_2) and nitrogen (N_2). "Gen" represents general facilities such as cooling towers, control rooms, and waste water treatment. All monetary values are on second quarter 2005 basis. "Total" represents "total plant cost" which excludes owner's costs, transmission lines, CO_2 pipeline, and other "off site" infrastructure. ITM = Ion Transport Membrane.

[4] "Potential for Improvement in Gasification Combined Cycle Power Generation with CO_2 Capture", IEA Greenhouse Gas R&D Programme, PH4-19, May 2003.

EPRI's Strategic Bridge Plan in this area lists the following R&D topics to address the need to improve the cost and reliability of IGCC plants while producing zero emissions and producing "sequestration ready" CO_2:

- Integration and testing of advanced CTs (G-class and H-class) on syngas (carbon monoxide and hydrogen together, and hydrogen alone) for reliability and low NO_x emissions
- Hazardous air pollutants (HAPs) characterization (particularly mercury) from a variety of gasifier designs
- Scale-up of transport reactor design
- Development of low-rank coal designs for higher efficiency
- High pressure solid feed to allow increased efficiency and integration of gasification
- Air separation unit advances through membranes or other technology
- Long-lived gasifier refractory to enhance reliability and reduce cost
- Membrane separation of hydrogen (H_2) and CO_2 at high pressure
- Integrated pilot testing of gasification with fuel cells
- High pressure and temperature heat exchangers to boost efficiency
- High temperature quench testing and demonstration
- Demonstration of integrated designs meeting criteria of high efficiency and less than $1300/kW
- Testing with "opportunity" fuels including partial biomass feed
- Power and fuel – designs for transportation fuel (e.g., hydrogen, dimethyl ether, methanol), heat and power

Advanced Coal Combustion Technology R&D

In pulverized coal (PC) units, the steam temperature is the primary driver of efficiency – raising the steam temperature increases efficiency. Today, new PC units with main and reheat steam temperatures of 1112°F/600°C are becoming the world standard for the lower-sulfur coals typical of the international merchant coal trade. In the United States, the prevailing higher sulfur and/or chlorine content in coal has led the power industry to limit design steam temperatures to somewhat lower levels (historically about 1050°F/ 565°C) due to concerns about liquid ash corrosion and other forms of damage to traditional ferritic steels.

Successfully raising the steam temperature in a PC unit is primarily a matter of developing materials that can consistently withstand the temperature. The U.S. Department of Energy (DOE), Ohio Coal Development Office, and a team comprising Energy Industries of Ohio, EPRI, Babcock & Wilcox, Alstom, Foster Wheeler, and Riley Power, assisted by Oak Ridge National Laboratory, have been conducting a USC boiler materials program aimed at developing and testing new alloys with superior high-temperature strength and creep and corrosion resistance.

This program, designed for the coals found in the U.S. market, especially eastern bituminous, has been underway for about six years. Researchers are finishing their first major work phase – which includes multi-year exposure of fabricated components in a power boiler at simulated ultrasupercritical (USC) conditions – and have accomplished almost all of their goals. New tasks have been added, and the culmination of work will be a dataset suitable for code qualification by the American Society of Mechanical Engineers, boiler insurers, and other standards-setting bodies. A new analogous program has been launched for USC steam turbine materials (with turbine manufacturers as the industrial partners).

Together, the USC material programs and associated design studies should enable commercial PC plants to be offered in the United States (and by extension, virtually everywhere else in the world as the U.S. has some of the most challenging coals) with efficiencies of higher than 45 percent in a single reheat mode and more than 47 percent in double reheat mode (HHV basis). Although the performance of these new units will be outstanding, further reducing CO_2 emissions from these plants requires integrated post-combustion capture technologies. The most efficient PC plants commercially available in North America today without CO_2 capture can attain annual average efficiencies of about 38 percent (HHV basis). Integrating carbon capture significantly increases the plant cost and reduces its efficiency. Table 3-2 shows potential improvements to bituminous coal-fired PC plants with post-combustion 90 percent CO_2 capture. Continuing to conduct R&D that enables development and deployment of increasingly higher temperature and higher pressure plants will overcome this cost and efficiency "penalty" for carbon capture. Like the R&D plan for IGCC, these advances are expected to result in a plant with 90 percent capture that is lower cost and higher efficiency than today's PCs plants without capture.

Table 3-2
Potential Improvements to Bituminous Coal-Fired Supercritical and Ultrasupercritical PC Plants With Post-Combustion 90 Percent CO_2 Capture

	SCPC (1)			USC + DRH (2)
	MEA (3)	KS-1 (4)	AC (5)	AC
Net power, MW*	335.3	406.4	448.8	458.4
Steam turbine loss, MW	88.8	59.3	21.7	17.7
COE, $/MWh	73.1	61.7	53.3	50.6
Avoided cost of CO_2, $/ton	34.8	22.0	12.1	9.2

(*) 500 MW without CO_2 capture; all costs in 2003 dollars

(1) Supercritical PC boiler: 3615 psia/1050°F/1050°F; conventional boiler design; tower capture plant design.
(2) Ultra supercritical PC boiler with double reheat; 5105 psia/1360°F/1400°F/1400°F; improved boiler design; membrane capture plant design.
(3) Monoethanolamine solvent; high heat of solvent regeneration; poor heat utilization; low CO_2 loading; 4 absorbers and 4 strippers.
(4) KS-1 solvent by MHI; improved amine with medium heat of regeneration; improved heat utilization; higher CO_2 loading; 2 absorbers and 2 strippers.
(5) Ammonium carbonate solvent; low heat of regeneration at elevated pressure reducing compressor size and power demand; improved heat utilization; 2 absorbers and 1 stripper

For regions where low-rank coal dominates, SC FBC may be the most cost-effective advanced coal option. Today's atmospheric fluidized-bed combustion plants, primarily based on a circulating bed, inherently reduce NO_x emissions because of their significantly lower operating temperature. Moreover, SO_2 is captured *in situ* with limestone, and ash deposition and fouling is decreased, compared to PC units. FBC plants are able to accommodate a much wider range of fuels than PC plants, with fuel lump sizes up to ½ inch. However, CO_2 capture may be more costly for these plants than for IGCC or PC plants.

EPRI's Strategic Plan in this area lists the following R&D needs to demonstrate USC PC and FBC systems with integrated boiler, turbine, and balance-of-plant designs, at temperatures of 1200°F/650°C, 1300°F/704°C and 1400°F/760°C:

- Establish material properties for new alloys: ferritic steels (1200°F/650°C); and new nickel-based alloys (more than 1300°F/704°C) to enable advanced steam conditions
- Establish material properties for metallic and ceramic heat exchanges
- Advance steam turbine designs including seals, bolting, and casings
- Develop material fabrication, machining, field installation, and repair techniques
- Examine functionally graded materials that can deliver the appropriate properties at the appropriate locations
- Explore shape memory alloys in sensors, actuators, circuit breakers, and transmission line sag control
- Improve understanding of chemistry properties, interaction with materials, and thermodynamics associated with new plants
- Explore and develop materials capable of handling bottoming cycles utilizing different working fluids (e.g., ammonia-water environment)

Improving the Efficiency and Extending the Life of the Existing Coal Fleet

Representing about 60 percent of the total power generation portfolio in the U.S., the existing aging fleet of conventional PC generating units is experiencing more demanding operating regimes, such as cycling duty. Hence, technology R&D must also focus on extending the life of this huge asset base.

Short-term gains in emissions reductions are possible via increases in plant efficiency. And these efficiency gains are closely linked to plant reliability. To realize these improvements, the technology from which critical equipment is designed, installed, operated, monitored, and maintained will require significant improvement over today's levels, and it must become more cost-effective to implement. At the same time, the effective integration of various optimized combinations of technologies is also needed. These gains will tend to shift the vertical line (that determines the point at which coal-based power generation becomes more cost-effective than natural gas-fired generation) to the left on the map of the four scenarios.

Technology R&D needs include the following:

- Improve understanding of the impact of off-normal operation on equipment reliability
- Factor "lessons learned" into design of replacement equipment and new generation equipment.
- Improve ability of operator and plant staff to assimilate and integrate reliability related information to make accurate decisions.
- Develop more sophisticated methods to reduce uncertainties and broaden applications to new materials and designs.
- Conduct maintainability and reliability studies combined with demonstration of critical equipment of new designs and materials to help determine emerging O&M concerns
- Conduct performance testing to determine extent of equipment degradation and drive cost-effective O&M decisions
- Develop improved basis, methods, and guidance for lay up, decommissioning, and recommissioning.
- Improve nondestructive evaluation (NDE) technology methods for better and more real-time assessments.
- Design specialized techniques and tools to inspect locations that are currently difficult or impossible to access.
- Improve NDE technology for commercial use.

Conclusions

Advanced coal power technology makes sense to varying degrees in three of the four scenarios. IGCC, for example, makes sense in either scenario with high natural gas prices (see Figure 3-2). In the "Digging in our Heels" scenario, which does not require CO_2 capture, technology R&D advances and additional experience with full-scale IGCC plants are needed to eliminate or at least reduce the higher cost of IGCC today, compared to PC. Yet even if IGCC plants remain marginally higher cost than PC plants, their strategic value if "Digging in our Heels" is a short-term scenario that shifts to "Double Whammy" is significant. The reason is that retrofitting CO_2 capture on a PC plant is much more expensive that retrofitting it in an IGCC plant.

In "Double Whammy," high natural gas prices favor coal-fired generation, and high CO_2 prices favor any generation technology that can cost-effectively capture CO_2. In this scenario, IGCC is advantageous when burning bituminous coal, if technology R&D reduces its capital costs, improves its efficiency, and demonstrates its reliability. When burning lower rank coals (e.g., sub-bituminous and lignite), IGCC and advanced PC are a "dead heat." Conversely, IGCC is not likely to be a key part of the generation mix in either the "Supply to the Rescue" or "Biting the Bullet" scenarios since low natural gas prices would not enable IGCC to be cost competitive.

Like IGCC, advanced coal combustion plants make most sense in either scenario with high natural gas prices. In the "Digging in our Heels" scenario, technology R&D advances in advanced combustion may lead to the most cost-effective power generation option of all. Advances in materials that enable more efficient operation on an abundant fuel source, without the demands of carbon capture, fit this scenario perfectly. SC FBC plants play an important role in this mix as well, making best use of low-grade coal. In the "Double Whammy" scenario, advanced coal combustion is better than conventional coal combustion, but not as clear of a winner. Here, materials R&D may enable advanced coal combustion plants to compete successfully with natural gas plants, nuclear, and other resource options in this scenario.

Extending the life and improving the efficiency of the huge existing fleet of coal fired power plants to reduce electricity costs (and in some scenarios, to reduce CO_2 emissions) makes sense in all four scenarios.

Key R&D Topics

Following is a list of the key R&D topics for the area of coal power technology:

- Extend life and improve efficiency of existing coal plant technologies
- Reduce capital costs and improve efficiency of Integrated Gasification Combined Cycle plants
- Reduce capital costs and improve efficiency of advanced Pulverized Coal plants
- Reduce capital costs and improve efficiency of Fluidized Bed Combustion plants
- Enable incentive trade-off analyses for early deployment of advanced power generation plants

Scenario	"Biting the Bullet"	"Double Whammy"	"Supply to the Rescue"	"Digging in Our Heels"
	High CO_2 prices Low gas prices	High CO_2 prices High gas prices	Low gas prices Low CO_2 prices	High gas prices Low CO_2 prices
Overview and drivers of technology R&D.	Emphasis on carbon capture in gas-fired plants & near zero emissions (NZE, except CO_2) in all fossil fired units; little or no IGCC or adv. combustion coal units	New IGCC and advanced combustion coal plants with carbon capture and near zero emissions (NZE), plus improved efficiency of existing coal plants	Emphasis on gas-fired generation with no carbon capture; less focus on reduced emissions; little or no IGCC or advanced combustion coal units	Emphasis on IGCC and advanced combustion coal plants without carbon capture (or staged capture)
Technology R&D Gaps: For each scenario, these represent the critical technology R&D needs in the area of coal power generation technologies. **Legend:** Very critical Critical Important Arrows indicate that the R&D need applies to *more than one scenario*	Extend life & improve eff. of existing coal fleet to reduce CO_2 emissions/power costs Enable trade-off analyses for early deployment of adv. coal	For IGCC, reduce capital cost to <$1300/kW and improve efficiency to ~45% HHV with 90% CO_2 capture and NZE For advanced pulverized coal, via materials advances, reduce capital cost to ~$1400/kW and improve efficiency to ~46% HHV with 90% CO_2 capture and NZE Reduce cost and improve efficiency of fluidized-bed combustion plants for low-rank fuels with NZE Extend life & improve eff. of existing coal fleet to reduce CO_2 emissions/power costs	Extend life & improve eff. of existing coal fleet to reduce electricity costs	For IGCC, reduce cost and improve efficiency without CO_2 capture; plan for potential retrofit of low-cost CO_2 capture For advanced pulverized coal, via materials advances, reduce capital cost and improve efficiency without CO_2 capture Reduce cost and improve efficiency of fluidized-bed combustion plants for low-rank fuels Extend the life and improve the efficiency of existing coal fleet to reduce electricity costs

Figure 3-2
EPRI Scenario and Technology Development Matrix for Coal Power Generation Technologies

Natural Gas Fired Generation Technologies

Overview

In the 1990s, natural gas fired combustion turbines (CTs) and combined cycles became the technology of choice for power production in the United States and other areas of the world where natural gas was available at relatively low cost. These machines offer the lowest investment requirements of any new type of commercially-available central station plant, are very efficient, have a small plant footprint, can be readily sited, and can be constructed in a much shorter period of time than other large-scale power generation options. Simple-cycle CTs are usually installed to meet peak power market demands. The largest CTs of this type have capacities of 150-200 MW and efficiencies of 35-40 percent (lower heating value, LHV). Higher efficiency combined cycles have current maximum capacities of 250-300 MW with efficiencies of 55-60 percent (LHV). These are normally selected for intermediate and baseload operation, although those equipped with duct burners (about 50 percent of new combined-cycle plants) can also be used for peaking duty.

Most CTs today are capable of near zero emissions of nitrogen oxides (NO_x), sulfur oxides (SO_x), carbon monoxide (CO), particulates, and hazardous air pollutants (HAPs) on natural gas through the use of ultra-low NO_x combustion with exhaust scrubbing systems. A number of manufacturers offer CTs in a mature market.

Primary R&D needs for CTs include increasing efficiency, enabling fuel flexibility (with syngas and liquefied natural gas [LNG] fuels), enabling turndown, and enhancing durability.

Increasing Efficiency

One way to increase efficiency in land-based turbines used for power generation is to increase turbine inlet temperature (see Figure 3-3). The most advanced aero-based turbines used in jet aircraft successfully operate at 3000°F/1650°C, but this is based on different time scales than are used in land-based turbines; military engines operate for only approximately 500 hours before requiring an overhaul, whereas this timescale is much longer for land-based machines. Today, the most advanced land-based turbines operate at 2600°F/1425°C. One key ongoing need is to migrate a broad range of advanced materials from military and civil aerospace engine development to land-based turbines. Barriers include repair limits, the proprietary nature of original equipment manufacturer (OEM) parts, and high production costs when scaling down from many small aircraft parts to few large land-based parts.

To withstand this higher turbine inlet temperature, advanced materials are needed. Substrate materials technology for turbine blades and vanes is migrating from the more traditional polycrystalline materials to directionally-solidified and single-crystal alloys. In the most advanced machines today, single crystal technology is in its second generation of use in land-based turbines, while military aerospace machines are in the fifth or sixth generation of this technology. Hence, more extensive adoption (via further development and demonstration) of these advanced materials technologies in land-based turbines is needed.

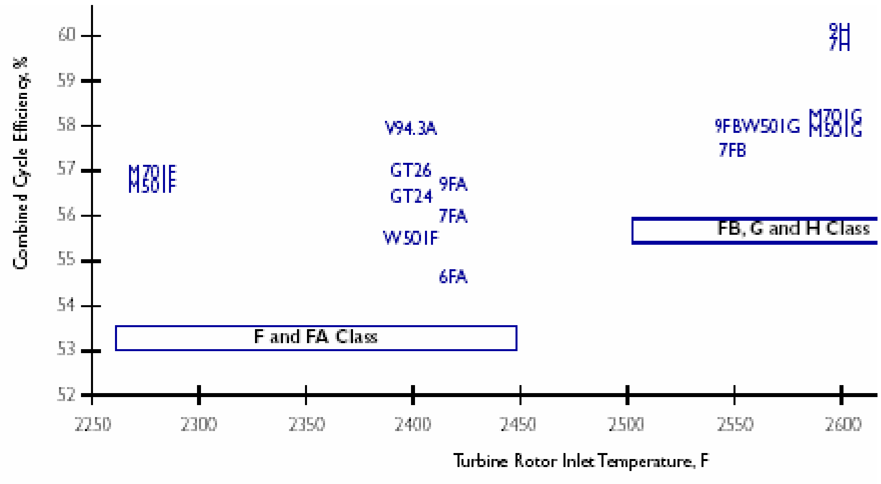

Figure 3-3
Increasing Turbine Rotor Inlet Temperature Tends to Increase CT Efficiency.

This plot shows the efficiency and inlet temperature of CT model numbers from CT manufacturers. Generally, the F-class (and slightly modified FA class) machines operate at lower temperatures and efficiencies than the FB, G, and H class machines.

Thermal barrier coatings (TBCs) present another way to increase turbine inlet temperature, when used in conjunction with internally cooled parts. As their name implies, the function of TBCs is to act as a thermal barrier. Because of their low thermal conductivity, they act to decrease the metal surface temperature. The decrease can be as much as 180°F/100°C. Research is needed on TBCs in those areas not being adequately addressed by the aircraft gas turbine industry. Since the aerodynamic and cooling designs of advanced land-based CTs differ from those of aircraft gas turbines, it is necessary to study the bond coat adherence and strain tolerance of different TBC process applications for land-based CTs. Nano-layering to improve thermal resistance, and alternate compositions to the basic stabilized Zirconium should be investigated.

Turbine inlet temperature can also be increased by improving component cooling systems. The most advanced cooling systems use steam as a cooling medium in some stationery and rotating parts. While the F-class CT is air-cooled, the more advanced G-class machine uses steam cooling in stationery transition pieces, and some H machines uses steam cooling in stationery components and the first stage of rotating blades.[5] Steam-cooled machines are designed for baseload, combined-cycle configuration, and rely on an integrated steam turbine bottoming cycle for cooling. But steam cooling introduces complexity and various issues, including material compatibility with the steam, steam purity and cooling air purity, integration with steam cycle

[5] Combustion turbines (CTs) are grouped in classes, based primarily on turbine inlet temperature. “F-class” machines are the most advanced class of CTs that are in widespread commercial service. Some higher temperature “G-class” and even higher temperature “H-Class” CTs are also now in commercial service. Each major turbine manufacturer produces a turbine or line of turbines in these classes.

and controls complexity, steam leakage, TBC durability, and others. Further work is needed to enable effective application of steam cooling to more components.

Efficiency can also be improved without increasing turbine inlet temperature. For example, the compressor itself plays a major role in the overall efficiency of the machine, because the compressor consumes a significant amount of the power of the CT. Even though compressor metallurgy is relatively “low tech,” R&D is needed to reduce the power consumption of existing axial compressor designs and to investigate alternative compressor designs such as those based on shock waves. Advances in this area may be first introduced at smaller scales (e.g., in smaller turbines or even microturbines). The challenge then would be to scale the new technology to the size needed for central station CTs.

In a related area, interstage cooling in compressors shows promise for capacity enhancement. Testing has shown that injecting water into an axial compressor can reduce the work of compression, reduce the compressor outlet air temperature, increase output power, and reduce NO_x emissions, but further work is needed to demonstrate this technology. Basin Electric has commissioned the first commercial intercooled machine – a General Electric (GE) LMS 100; the cost and reliability of the large heat exchangers needed is a key R&D issue.

Improved seals – another technology that is being transferred from flight engine designs to land-based CTs – also improve efficiency by reducing parasitic leakages, affording improved control of the secondary flow system, and helping offset performance degradation at part-load operation. This results in significantly improved performance in efficiency (heat rate) and power output. Seals are migrating from honeycomb, brush, abradable, and adjustable to more effective compliant abradable, hydraulic, and adaptive types (see Figure 3-4).

Improvements in the design of the components themselves in the turbine hot section can also improve efficiency. To this end, further advances in three-dimensional aerodynamic design of blades and flow passages are needed.

Fuel Flexibility

The current CT technology is designed to operate on a homogeneous natural gas fuel supply. Deviating from this fuel supply causes a range of challenges, including placing at risk the sophisticated metallurgy used in advanced CTs today. With high natural gas prices today and the push to develop and demonstrate integrated gasification combined-cycle (IGCC) power plants, CTs are needed in the IGCC that can be fueled by the resulting syngas – the fuel derived from coal. The syngas may also be piped (and mixed with other fuels along the way) to the sites of existing CT plants for combustion.

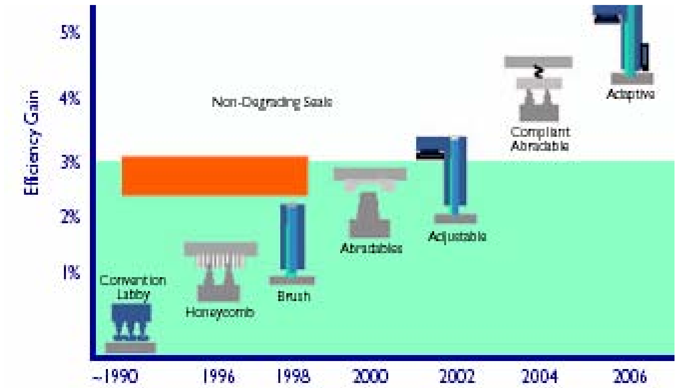

Figure 3-4
In this progression of advanced seal development to date, the non-degrading seals (above the shaded area) significantly reduce wear using springs or hydraulics that adjust for shaft movement

However, operating these CTs on syngas today causes a step backward in technology. For one reason, existing dry low NO_x (known as DLN) combustors cannot accommodate this fuel. These combustors must operate within tight tolerances of equivalence ratio, fuel/air mixing, and turbulence in order to deliver single-digit NO_x emission performance, while maintaining combustion stability and design power output. Lean pre-mixed DLN combustor designs are not appropriate for the hydrogen (H_2) content of syngas, because of the high flame speed of H_2 combustion and the danger of flashbacks, catastrophic turbine damage, and risks to personnel and other equipment. Therefore, older technology – diffusion flame combustors – is used, in which the blended syngas fuel (H_2 and nitrogen, N_2) and the steam for NO_x control are injected separately into the combustion air.

In addition, burning any fuel that contains more H_2 creates more water vapor, which tends to create more heat transfer, which increases the metal temperature. Because of limitations of the metallurgy and other factors based on metal temperature, burning a fuel that contains more H_2 causes a step backward to older technology. This can lead to compromises in efficiency, emissions, and other performance measures. This calls for R&D to develop a different type of combustion system – a lean premixed combustor that is not based on flame diffusion (e.g., catalytic combustors, trapped vortex burners that originated in military development). The economics of such an advanced low emission combustor is closely tied to selective catalytic reduction (SCR) for NO_x control; if additional conditioning of the flue gas is required to remove potential catalyst poisons and maintain the effectiveness of the SCR system, then the economics would favor an advanced low emissions combustor that can provide this conditioning.

Even within the spectrum of natural gas fuels, introduction of liquefied natural gas (LNG) may cause fuel interchangeability problems. The international standard for LNG is much broader than the domestic standard for natural gas, leading to a wider variability in the fuel. DLN burners need to be tuned to a specific operating condition and do not function properly with high hydrocarbons or liquids. Hence, R&D is needed to develop a combustor that can accommodate a broader range of fuels.

A closely related issue is CT turndown – the ability to operate the CT efficiently at partial load. The changing mission of CTs as fuel prices and other factors change may require operation of CTs in operating modes that are different than their design specifications. Out of the box, today's typical CT can only be operated down to 70 percent of rated load, and additional measures can be adopted today to reduce this level to 50 percent. However, this turndown capability is predicated on a well characterized, homogeneous fuel. Operating on a different fuel mix can adversely affect this turndown capability and lead to flashbacks and blowouts. When the units are turned down, emission levels can also rise. Hence, fuel variability can also affect emissions levels. Hence, R&D is needed to examine alternatives that will enable high turndown, while maintaining efficiency and emissions control.

In a combined-cycle arrangement, burning syngas causes other complexities. For example, in the heat recovery steam generator (HRSG), burning syngas can adversely impact the CO/NO_x catalyst. Further, a larger HRSG may be needed to accommodate the larger CT exhaust flow. (Syngas has a much lower volumetric heating value – 300 Btu/scf – compared to natural gas – 21,200 Btu/scf. Hence, a much larger volume of syngas is required to fire the CT at its full rating.)

Historically, problems like these have been addressed by reverting to older technologies. For example, additional NO_x control may be needed as a result of burning syngas instead of natural gas. The air separation plant at an IGCC plant uses a cryogenic process to remove nitrogen from air to form pure oxygen that is needed for the gasification process. The resulting nitrogen can be used as a source of dilution as part of the NO_x control system. However, if syngas is piped to a remote existing CT plant, where no air separation plant exists, other means of maintaining single digit NO_x emissions levels would be necessary. Further, if an advanced membrane system is used to provide the needed oxygen at an IGCC plant, the nitrogen stream would not exist for use in NO_x control. So gains in some areas may cause problems in other areas. R&D to address these complexities is needed.

Another key element in CT power plants involves the ability to capture CO_2. Refer to the section on carbon capture and sequestration for more information.

Durability

When blades deteriorate beyond repair due to excessive base metal damage, turbine owners can incur replacement costs of $2-3 million per row. If a blade breaks off during operation and causes extensive downstream damage, the replacement cost of the hot section components alone can exceed 25 percent of the cost of a new unit. Failure and maintenance costs are compounded when affected turbines are unavailable, primarily because producers must either dispatch less efficient turbines, purchase replacement power, or lose income during lucrative load periods. Unavailability can cost turbine owners up to $500,000 per day in lost revenues for a 500-MW combined-cycle plant.

To help reduce blade failures, a class of coatings is used to protect turbine blades and vanes from various forms of corrosion, oxidation, and thermal-mechanical fatigue cracking. Failure of these protective blade coatings represents a major profitability challenge for CT owners. Coating life usually dictates blade refurbishment intervals, which typically are shorter than desired, and downtime for coating inspection and refurbishment requires dispatch of less-efficient generating equipment or purchase of replacement power. However, conservatism is warranted when refurbishing coatings; coating failure can lead to rapid, severe damage to the superalloy substrate.

Coating technology has evolved from simple diffusion aluminides to more complex dual-layer metallic coatings. No single coating can be universally applied to all CT blades. Selection of a coating depends on a host of factors, including the purity of fuel and air entering the machine, the type of corrosion encountered, the mode of turbine operation, the strain ranges imposed, and the expected metal temperatures at the specific location. Diffusion aluminide coatings are also used on some hot section components to protect the internal cooling passages inside the blades from oxidation. Application of these coating on internal passages began with military and civil aero engines and their aero-derivative industrial counterparts. To enhance reliability of turbines and extend time between overhauls, advances in blade and vane coatings are needed. A further area of needed R&D is the interaction of TBCs with these metallic coatings, especially TBC adherence to the metallic coatings at the interfacial boundary.

The ability to repair, rather than replace, the expensive components employed in the hot section of modern CTs can substantially reduce overall lifecycle costs. Repairs of CT blades are currently limited to the upper tip region of the airfoil where operating stresses are commonly low. This limitation is predicated upon the use of low strength welding filler materials and the use of high-energy welding processes such as gas tungsten arc welding. When blade damage is located within parts of the airfoil subjected to higher stress levels, blades are often scrapped or replaced, costing generators millions of dollars each year. Advanced techniques that allow repairs at higher stress regions of the blade airfoil could significantly reduce the need and costs of scrapping components.

New monitoring and nondestructive evaluation techniques are needed that address key knowledge gaps. For example, optical pyrometry, now widely used in commercial aircraft, continues to struggle for broad acceptance in land-based engines. Originally developed to measure CT blade temperatures in aircraft engines, optical pyrometers have become a vital tool in the development of modern, high-temperature gas turbine engines for military and commercial aircraft. In contrast to land-based engines, aircraft engines typically see only short periods of full-load operation (during take-off and landings), have less flexibility to alter regulated maintenance practices, and often have a much larger population of engines from which to derive risk-based maintenance inferences. Pyrometry may have an opportunity to provide safety and life management roles in land-based engine operations due to these specific O&M differences. Barriers include high cost, technical limitations related to line-of-sight, and limitations with ceramic coated blades.

At the same time, introduction of new technologies at an increasing rate to achieve higher firing temperatures and improved efficiencies inherently involve risk related to design limitations and life-cycle performance. For example, new design deficiencies include the susceptibility of certain designs to rotor vibration, foreign object damage, and burner instability. Life-cycle issues include performance degradation and accelerated consumption of the material life of hot-section parts. Tools are needed to enable improved risk assessment and decision making for the procurement process.

Advanced Cycles

The potential benefits of humid air injection have been studied for many years as humid air turbine (HAT) and cascaded humidified advanced turbine (CHAT) cycles. The goal of these cycles is to significantly improve cycle efficiency by increasing the water content of the air in various parts of the cycle. Initial testing of a retrofit approach in 2003 has shown that the technology is promising, but costs are high and there is a need for demineralized water in the tested configuration. Figure 3-5 shows a new approach for simple-cycle CTs that is expected to lead to lower costs and avoid the need for demineralized water. This approach eliminates the need for a large custom-engineered saturator and uses developed components. This concept can also be applied in a combined-cycle arrangement. Additional R&D is needed to advance HAT/CHAT technology, which has not yet been commercially demonstrated.

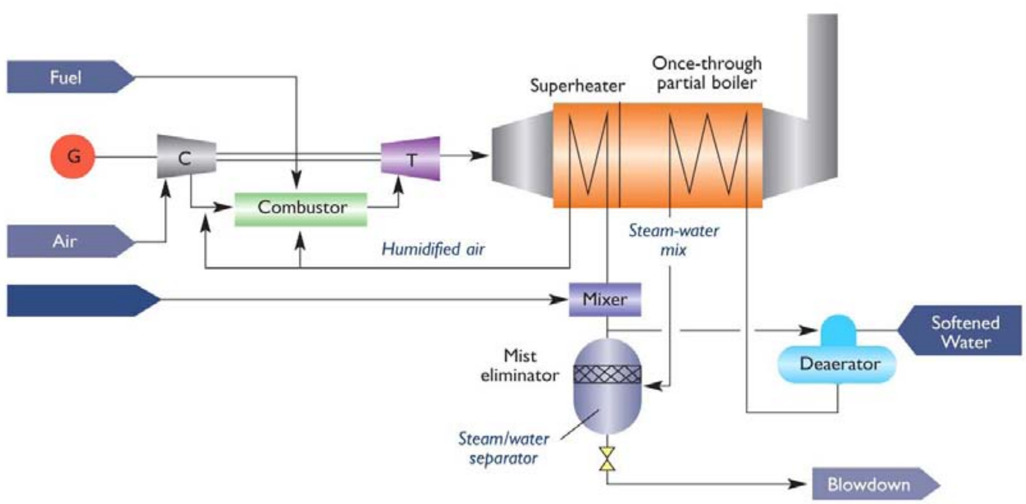

Figure 3-5
CT Humid Air Injection With Once-Through Partial Steam Generator. Source: Nakhamkin, et al., "Humid Air Injection."

Conclusions

Many technological advances in large CTs are likely to originate first either in the military or civil aerospace sector or in the distributed generation area. Regarding the former area, the challenge is to adapt these advances to the demands of land-based machines. Regarding the latter, fierce competition among multiple manufacturers is likely to result in advances in compressor design, efficiency, and advanced cycles. The challenge here is to scale up these advances to meet central station needs.

With respect to the four scenarios and the role of CTs, a careful look leads to some interesting conclusions (see Figure 3-6). In the "Digging in our Heels" scenario, high natural gas prices provide a disincentive to increase reliance on CT-based power plants. However, movement to any of the other three scenarios would increase the value of CTs. For example, a shift to high CO_2 prices would effectively lower the natural gas cost. The reason is that natural gas plants inherently produce less carbon dioxide (CO_2) per BTU, compared to coal, because of the chemical reaction of methane. This provides CTs a strategic edge in a carbon constrained world.

The value of CTs skyrockets in the "Biting the Bullet" scenario. Here, low natural gas prices, which favor CTs and high CO_2 prices provide a dual benefit of natural gas fired power plants. This is the most favorable scenario for CTs. Even in the "Supply to the Rescue" scenario, natural gas-fired power plants would be more valuable than they are today. For in this scenario, low natural gas prices enable CTs to compete favorably with every other power generation option.

One wild card in this analysis is the uncertain availability and price over time of LNG. Varying availability of LNG will lead to price fluctuations in natural gas, impacting which scenario is dominant over time.

Key R&D Topics

Following is a list of the key R&D topics for the area of natural gas fired generation technology:

- Improve CT/CC turndown efficiency across load range
- Increase CT/CC efficiency via higher turbine inlet temperature operation
- Improve CT/CC components (e.g., by improved coatings, adv. repair and new diagnostics)
- Enable CT/CC to run efficiently on <u>mix</u> of North American gas and liquefied natural gas
- Develop and evaluate advanced CT/CC cycles to lower capital and operating costs
- Explore nano-coatings for high temperature turbine blades
- Address gas-electric infrastructure interdependencies that impact forced outages
- Conduct fuel-electric system integration analysis with security of electric infrastructure

Scenario	"Biting the Bullet"	"Double Whammy"	"Supply to the Rescue"	"Digging in Our Heels"
	High CO_2 prices Low gas prices	High CO_2 prices High gas prices	Low gas prices Low CO_2 prices	High gas prices Low CO_2 prices
Overview and drivers of technology R&D	Best scenario for CTs; higher efficiency than coal technologies capitalizes on high CO_2 prices	Good scenario for CTs; higher efficiency than coal technologies capitalizes on high CO_2 prices	Good scenario for CTs; low gas prices enables CTs to compete with other power generation options	Worst scenario for CTs; high gas prices and inability to differentiate with coal stifles new CT plants
Technology R&D Gaps: For each scenario, these represent the critical technology R&D needs in the area of natural gas fired generation technologies.	Solve challenges of operating existing and new CT/CC on mix of domestic gas, *LNG* Increase CT/CC efficiency Improve carbon capture from gas-fired plants Improve turndown (eff. across load range) Improve durability of CT/CC components via improved coatings, advanced repair, new monitoring & diagnostics, & improved risk assess Investigate adv. Cycles Explore nano-coatings; address gas-electric interdependence; conduct integrated security analysis	Solve challenges of operating existing and new CT/CC on mix of domestic gas, *syngas*	Solve challenges of operating existing and new CT/CC on mix of domestic gas, *LNG*	Solve challenges of operating existing and new CT/CC on mix of domestic gas, *syngas*

Legend:
Very critical
Critical
Important
Arrows indicate that the R&D need applies to *more than one scenario*

Figure 3-6
EPRI Scenario and Technology Development Matrix for Natural Gas Fired Generation Technologie

Existing Nuclear Power

Overview

Nuclear power provides a significant portion of electricity generation throughout the world. Meeting the electricity needs of nearly 1 billion people in over 30 countries, the nuclear power industry has demonstrated that electricity can be reliably produced without contributing to global climate change or emitting other significant pollutants. In fact, a number of industrialized nations rely on nuclear power to provide half or more of their electricity.

The safety and economic performance of the existing fleet of nuclear power plants in North America is excellent overall. Despite high safety performance and record-setting reliability, materials aging and equipment obsolescence will power technical challenges that erode profitability. Continued high performance will be maintained via 1) strategic decision making and safety-focused plant management, and 2) new technology solutions that maintain high plant availability, economic performance, and competitiveness, while maintaining high levels of safety. Plant operators and engineers will also need to address the growing challenges of an aging workforce.

Needed R&D must combine incremental design improvements to critical equipment; innovative lower-cost alternatives for inspection, condition assessment, remaining life prediction, and maintenance; and proven, risk-based repair and replacement strategies. Near-term goals include extensive equipment reliability programs; development of technology to provide nuclear fuel that will meet performance requirements in the coming decades; industry leadership in addressing reactor vessel and internals issues; technology to demonstrate the adequacy of steam generators with service-related degradation; a proven license renewal process; and improved technology for low-level and high-level radioactive waste management. These R&D needs for existing plants can be grouped in the following nine categories:

- Materials degradation/aging
- Fuel reliability
- Radioactive high level waste and spent fuel management
- Nondestructive evaluation (NDE) and material characterization
- Equipment reliability
- Instrumentation and control hardware and systems
- Nuclear asset-risk management
- Safety risk technology and application
- Low level waste and radiation management

Materials Degradation/Aging

The economic realities of today's electric power market almost require nuclear power plants to achieve capacity factors in excess of 90 percent on a routine, continuing basis; and many of the existing nuclear plants in the U.S. have been able to meet this goal in recent years. However, maintaining this level of performance may become more difficult in the future because, as the existing nuclear plants continue to age, slow-to-develop (or incompletely mitigated) forms of materials degradation may increase the likelihood of significant component damage with increasing service time. This could lead in turn to an increasing likelihood of adverse consequences (e.g., plant derating, forced or extended outages, and higher operation and maintenance costs) with increasing plant age. For plants approaching license renewal, assuring regulators of the continuing reliability of plant components and safety-related systems adds another dimension to this problem. Thus, the cost-effective management of materials degradation and plant aging is likely to pose a continuing major challenge to the U.S. nuclear power industry throughout the remaining life of existing plants.

The rates of materials degradation, and the time-dependence of the consequent damage to plant components and systems, are strongly dependent on details of the local operating environment such as temperature, radiation types and fluxes, and water chemistry. Accordingly, the anticipated operating environment is a critical element of materials selection for new and replacement components. For components already in service, understanding how the operating environment can practically be modified is essential to cost-effectively mitigating degradation and avoiding its associated problems. Thus, a comprehensive integrated understanding of materials degradation and management options to address it are needed to develop overall plant business and operating strategies. R&D is needed to better understand and manage materials degradation/aging phenomena in major metallic components in existing nuclear power plants, particularly passive components in the reactor coolant systems of both boiling water reactors (BWRs) and pressurized water reactors (PWRs).

R&D is needed to overcome the following barriers:

- Limited mechanistic understanding of environmentally-assisted cracking.
- Lack of an integrated approach for managing PWR steam generator materials performance issues.
- Lack of an integrated, proactive approach for managing materials degradation in reactor coolant system components in BWRs.
- Lack of an integrated, proactive approach for managing materials degradation in reactor coolant system components in PWRs.
- Incomplete understanding of the effects of some light water reactor chemistry variables.

R&D is needed to:

- Develop strategies that enable plant operators to inspect, assess, mitigate, and repair stress corrosion cracking in core shrouds, other major internal components of reactor vessels, and primary-pressure-boundary piping.

- Provide the technical bases for resolving four pressing issues in PWRs: Alloy 600 nozzle cracking in reactor vessel head and piping penetrations, internals cracking, reactor pressure vessel integrity, and piping fatigue damage.
- Address the potential of materials cracking throughout the reactor coolant system, and evaluate consequences, inspection, mitigation, and repair for susceptible locations and components.
- Improve the useful life of BWR and PWR primary system components by gaining a better understanding of the crack initiation and early propagation processes involved in stress corrosion cracking and irradiation-assisted stress corrosion cracking.
- Determine the root cause(s) of various forms of steam-generator degradation; develop mitigating actions; provide input to replacement steam-generator specifications; establish guidelines for water chemistry, in-service inspection, and tube integrity; develop and validate nondestructive evaluation methods; and respond (along with the Nuclear Energy Institute) to Nuclear Regulatory Commission (NRC) steam-generator-related requests.
- Develop and test advanced chemistries, tools, and guidelines for improving water chemistry control.
- Define, on a plant-specific basis, optimized chemistry programs to reduce corrosion damage and the release of corrosion products into coolant systems and to mitigate the impact of chemistry-related problems on plant safety, operation, and profitability.

Fuel Reliability

While fuel reliability has improved over the last few decades, significant concerns remain as the overall industry fuel failure rate actually increased in the early 2000s. Some of the experience has been attributed to trends of increasing fuel duty, extended fuel cycle operation, and new water chemistry environments. In many cases, decisions for fuel cycle (front-end) economics and fuel reliability are simply at odds. The end result is that operating margins have been reduced without quantifying these margins.

R&D is needed to:

- Focus on PWR fuel corrosion and crud control, including providing solutions for axial offset anomaly experienced in many high-power PWRs
- Respond to issues such as potential changes to reactivity-initiated accidents, loss of coolant accident criteria, and development of an industry guide for burn up extension.
- Evaluate operating margins under high-duty conditions (poolside and hot cell examinations for both PWRs and BWRs)
- Conduct fuel failure investigations and other R&D related to fuel and core component reliability, such as control rods
- Address fuel corrosion and crud control issues in BWRs

Radioactive High Level Waste and Spent Fuel Management

The development of a spent (used) nuclear fuel and high-level waste repository is critical for the continued viability of nuclear energy and is an enabling condition for new plant orders in the United States. The U.S. Nuclear Regulatory Commission holds periodic “waste confidence” hearings to confirm that there is a viable national program to provide a permanent solution to high-level waste. The lack of a viable solution for disposing of used nuclear fuel would likely cause the Nuclear Regulatory Commission to lose confidence, thereby closing the door on future use and development of nuclear generation.

In the United States, the federal government is obligated to dispose of spent nuclear fuel. The federal disposal obligation originated with the 1954 Atomic Energy Act and has been reinforced in subsequent laws, most notably the Nuclear Waste Policy Act and its amendments. However, the federal government missed a 1998 statutory and contractual deadline to begin accepting spent fuel from nuclear power plants.

Because of delays experienced in opening a disposal facility, increasing amounts of spent fuel are being placed in interim storage. Due to limitations in spent-fuel pool storage capacity, licensees are increasingly relying on interim storage in dry container systems. However, several issues (e.g., cladding integrity, criticality, and security) have the potential for significantly extending the lead times for container certifications/license amendments and for implementing successful dry storage campaigns in a timely and cost-effective manner. Unless these issues are resolved, utilities will be economically penalized, and potentially severely restrained, in their ability to operate their nuclear plants.

Transportation of spent fuel from reactor sites to the proposed spent-fuel and high-level waste disposal site in the United States (i.e., Yucca Mountain, Nevada) or to central interim storage facilities (e.g., the proposed Private Fuel Storage facility) has become an actively contested activity. Public and congressional discussions related to the Yucca Mountain Site Recommendation process have highlighted the high degree of concern surrounding the transportation of spent fuel from all areas of the country to Nevada.

R&D needs include the following:

- Achieve a positive and timely regulatory decision on the proposed repository based on the scientific evidence supporting permanent spent-fuel disposal in Yucca Mountain’s geologic formation
- Establish the technical basis for resolving generic spent-fuel storage and transportation issues impacting plant operability (loss of full core discharge), license renewal of independent spent-fuel storage installations (dry storage beyond 20 years), and timely decommissioning
- Establish risk-informed approaches to improve regulatory efficiency for spent-fuel storage and transportation systems
- Enhance the technical basis for, and public confidence in, safely moving spent fuel off nuclear plant sites.

Nondestructive Evaluation and Material Characterization

Nondestructive evaluation (NDE) plays many and varied roles. An understanding of these roles helps define the contribution that NDE can make towards accomplishing strategic objectives. NDE serves three main functions in the nuclear power industry:

- Pre-service and periodic in-service inspection of components to satisfy regulatory requirements
- Inspection to characterize component condition
- Inspection to guide strategic decisions on whether and when to replace, repair, or continue operation of components

NDE includes developing and implementing advanced inspection technology, as well as using performance-based and risk-informed methodologies to do the following:

- Improve inspection reliability
- Increase the accuracy of information used to assess material condition
- Lower operating costs
- Lower radiation exposures to workers
- Help plant owners meet regulatory commitments.

Certain materials and certain conditions of access and geometry preclude NDE from achieving its objectives. NDE of austenitic welds is one example of an imposing technical challenge. Geometric conditions that prevent adequate contact with the surface likewise interfere with adequate NDE. As plants age, degradation is becoming more evident, challenging NDE technology to address newly discovered damage forms and introducing more pressure to address emerging issues. Even if NDE could meet all current code and regulatory criteria, these may not be adequate to address aggressive damage mechanisms such as primary water stress corrosion cracking. When these aggressive degradations form active areas, degradation can progress at such a rapid rate that NDE is challenged to detect and accurately size degradation when it is very small, allowing adequate time for corrective actions. Hence, aggressive R&D is required to address these limitations of capability.

Equipment Reliability

Equipment reliability encompasses and binds existing functions and programs into a single process, including performance monitoring and corrective action, preventive maintenance, long-term planning, and others. The full process is captured in Institute of Nuclear Power Operations (INPO) AP-913, *Equipment Reliability Process Description*. R&D needs include the following:

- Address material and equipment condition degradation, particularly unanticipated degradation, via 1) proactive identification of new generic degradation issues and responses, and 2) effective ready-to-use solutions for known degradation issues

- Address inadequate "early warning" physical indicator information via 1) methods to identify, observe, and monitor equipment physical indicator data; and 2) ability to process and understand indicator data, perform rapid component/system material condition assessments, and understand material-environment compatibility to yield actionable conclusions
- Address loss of key technical staff expertise due to plant staff reductions and staff turnover by 1) making key knowledge needed by technical staff available in ways that reduce the effort to extract and use the information, and 2) understanding the basis for today's equipment reliability activities and redefining the execution to integrate or simplify the implementation of the activities
- Address insufficient understanding of plant operational and maintenance change impacts via 1) cause-and-effect tools for assessing plant operational and maintenance changes, and 2) change-effects monitoring and experience assessments
- Address lack of involvement of plant staff in long-term planning via 1) identification of enabling processes that involve plant staff in the plants long-term planning activity, and 2) awareness of business planning needs
- Address resource limitations for implementing and integrating new technology by 1) improving new technology resource utilization and 2) scoping and evaluating technology alternatives, and pre-qualifying solutions
- Address operation of the equipment reliability process as a set of discrete activities via 1) process optimization support, 2) software tools to facilitate implementation of equipment reliability activities and interfaces, and 3) indicators that measure process effectiveness

Instrumentation and Control

Instrumentation and control (I&C) systems and capabilities affect all areas of plant operation and can profoundly impact plant reliability, efficiency, and operating costs. Most, if not all, nuclear power plants now have problems with aging and obsolete equipment, and these problems will be exacerbated as plants extend their operating licenses. With plant life extension, long-term maintenance of obsolete equipment is often not a viable alternative. I&C modernization strategies extend beyond like-for-like replacements of obsolete components. They include consideration of ways in which updated I&C equipment and functionality can be used to better support plant O&M. For example, modern sensors using updated data communication and analysis capabilities can provide on-line monitoring for condition-based predictive maintenance capabilities that improve equipment reliability and reduce the likelihood of forced outages.

Modern I&C equipment extensively uses microprocessor and other digital-based technologies, which are rapidly evolving and expanding their capabilities. Data communication, analysis, computerized support systems, display, and automation capabilities of new technology can spread the benefits of I&C modernization far beyond the traditional I&C boundaries. Owner/operators will need to consider every advantage made possible by technology as they strive to increase availability, reliability, and productivity, while reducing plant and fleet-wide costs.

The primary R&D need in the I&C area related to existing plants is to maintain and upgrade I&C systems and equipment to take full advantage of technology to reduce O&M costs, increase human performance, and increase power production, while maintaining or enhancing safety. Anticipated benefits include information-, systems-, and equipment-related improvements in plant availability, reliability, and performance, as well as in human performance. Additional benefits include process/organization-related improvements in efficiency of operations, maintenance, and engineering activities.

Nuclear Asset-Risk Management

Asset management is the process for making resource allocation and risk management decisions at all levels of a generation business to maximize value/profitability for all stakeholders while maintaining plant safety. Nuclear Asset/Risk Management focuses on economics and strategic decision-making, while equipment reliability focuses on managing and maintaining physical assets (equipment and structures), including life cycle management. Nuclear Asset/Risk Management demonstrates the impact of value- and risk-informed considerations for plant valuation and technical/strategic decision making to improve productivity over a selected time period, which can be the entire remaining operating term of nuclear power plants.

R&D is needed to overcome the following barriers:

- Lack of a cost-effective global robust risk-informed asset management/business model
- Inadequate databases of reliability and cost data
- Need for leading business performance indicators that enable enhancement and tracking of plant/fleet value

With regard to the first barrier, processes, methods, analytical models, and software tools are needed to support plant and corporate strategic asset management, including risk-informed asset management analysis and decision making. Technology is also needed to improve and facilitate business decision-making in light of uncertainty and risk (e.g., economic, asset, and safety risks). Because plant generation productivity is a main driver of economic performance, electricity generation (capacity factor) risk associated with the condition and performance of systems, structures, and components over the remaining operating term of plants must also be addressed.

Conventional business models and processes that value plants and prioritize projects could benefit from the enhancements needed to address the following issues that are becoming more important in a market-driven environment:

- Strategies to maximize return on investments in plant performance via capital and operations and maintenance projects
- Long-range planning related to predicted or unexpected equipment degradation issues, and aging workforce issues
- Balance between long-term and quick payback planning
- Uncertainty in electricity price forecasting and other market perspectives

- Influence of “soft” external value drivers
- Global vis-à-vis local thinking
- Risk-informed vis-à-vis deterministic asset management approaches
- Impact of future equipment failures on plant production

With regard to the second barrier, robust business models require robust input data. Unlike European plants, a major limitation in the U.S. is that plants do not pool reliability databases. Although all plants track reliability data for safety equipment in probabilistic risk assessments, reliability data for aging non-safety equipment important to generation is needed to optimize investments in life-cycle planning, maintenance, and capital improvements. Experience in applying life-cycle management in operating plants has revealed how difficult it is, without standardized cost accounting and automated plant databases, to assemble complete long-term costs of managing physical assets. The Nuclear Energy Institute is encouraging a shift to activity-based costing, but the shift is difficult, and more effort is needed to make it a norm in the industry.

With regard to the third barrier, key performance indicators established by various agencies generally focus on safety and reliability rather than including financial viability as a critical goal. Business performance indicators allow utilities to integrate risk-informed asset management and forecast future plant and utility performance using common metrics. The drivers of value should be ranked so that resources are not wasted tracking less important indicators. Risk-informed asset management tools can help to do this importance ranking and then focus on the main value drivers as they are applied to prioritizing plant investment opportunities.

Safety Risk Technology and Application

Risk-informing nuclear plant regulations, and the corollary, risk-informing nuclear plant operations, is a strategic objective of NRC, the U.S. Department of Energy (DOE), and the nuclear power industry. These areas are recognized as essential for long-term safe, reliable, and cost-effective operation of existing plants. R&D is needed in this area to address the following barriers:

- Probabilistic risk assessment (PRA) tools are resource-intensive, can yield inconsistent results, and are not uniform with respect to all initiators and plant operating states. Decision-makers lack confidence in their quality and adequacy for licensing applications. PRA and risk assessment tools, including computational software, decision analysis methods, and information management aids, need to evolve and be validated.
- The process for development and implementation of risk-informed/performance-based regulatory changes is inefficient and uncertain. The technical issues that impede acceptance and regulatory approval of useful, timely, and cost-effective improvements must be addressed, and implementation of risk-informed applications is needed.

- A strong risk management culture must be developed and sustained both at nuclear plants and at NRC to support successful widespread risk-informed/ performance-based regulation and operations. R&D is needed to develop risk management processes and tools (including both configuration risk management and performance monitoring) needed by plants to support risk-informed/performance-based regulations and operations. R&D is also needed to implement risk-informed programs such as for fire protection, special treatment of safety-related equipment, and risk-informed technical specifications.
- A robust, risk-informed regulatory framework does not exist for new plants. R&D is needed to develop and implement an objective and integrated framework for new plant regulations, which will take full advantage of risk-informed/performance-based decision-making.
- Competent risk analysts and risk management knowledge among nuclear professionals is needed. R&D is needed to define qualifications, identify educational resources, and provide new resources where critical gaps exist.

Low Level Waste and Radiation Management

R&D work in the area of low level waste and radiation management is needed to address three barriers. The first barrier is that current options for the management of low level waste and radioactive materials are neither assured nor optimized to meet changing requirements. R&D needs in this area include the following:

- **Low level waste generation.** Needs include enhanced options to minimize the volumes and cost of radioactive low level waste generation.
- **Low level waste disposal solutions.** Needs include maintaining class B-C disposal and storage options, defining clearance options and practices, and maintaining transportation viability while implementing new transportation security rules.
- **Radioactive materials management tools.** Needs in this area are information technology (IT) tools necessary to more cost effectively manage processing activities.

The second barrier is that current radiological protection (RP) strategies are inadequate to effectively meet changing future requirements and targets. Nuclear plant operators are required by regulations to maintain radiation exposures to personnel to values that are as low as reasonably achievable (ALARA). R&D needs in this area include the following:

- **Short-term reduction solutions.** There is a strong industry need for technology R&D in the field/source term reduction area. The RP2020 initiative has identified long term reductions in source term and radiation fields as a top priority.
- **Dose reduction technology solutions.** The industry is expected to be continually challenged with staff reduction pressures, optimization pressures, and dose reduction technology and strategy demands arising from the desire for shortened outages. For example, complex, potentially dose-intensive jobs are being performed during critical path timelines in refueling outages. Additionally, new material inspection and mitigation requirements pose significant ALARA challenges. This drives a technology need for advanced ALARA/RP planning and monitoring tools, as RP managers are required to support these jobs while continually decreasing worker exposure.

- **RP management tools.** There is a lack of industry IT/software innovation available to RP and ALARA teams. Needs exist for advanced dose planning and monitoring tools, and for industry-wide dose record and ALARA training technology standards so that workers can easily transfer records from site to site. More sophisticated approaches to realistically assessing worker risk arising concurrently from radiation and non-radiation (e.g., heat stress) effects are needed. Further, the industry is challenged by a lack of guidance on the clearance of radioactive materials from power plants.

The third barrier involves plant decommissioning. R&D needs in this area include minimizing the cost and risks of decommissioning through enhanced planning, applying lessons learned by other utilities with retired plants, and using advanced technology. Guidance is needed on unresolved issues in low-level waste management, site characterization, radiation dose modeling for site release, and license termination plans. Anticipating and addressing the needs of utilities facing premature (unplanned) shutdown of nuclear units in the future is an important goal. Capturing the lessons learned from current decommissioning work at power plants and archiving for future use is also needed.

Key R&D Topics

Figure 3-7 summarizes the critical R&D needs for existing nuclear power. Because the continued safe, reliable operation of the aging existing fleet of nuclear power plants is such a critical part of the electricity infrastructure in any case, these R&D needs are less sensitive to the scenarios than R&D needs in other categories. These R&D needs are also listed below:

- Improve plant reliability and efficiency (e.g., by reducing materials degradation and improved fuel reliability)
- Develop integrated spent fuel management system
- Identify role of technology in a work force constrained future
- Improve management of low level waste and radioactive materials
- Develop cost-effective, risk-informed asset management and business models

Scenario	"Biting the Bullet" High CO_2 prices, Low gas prices	"Double Whammy" High CO_2 prices, High gas prices	"Supply to the Rescue" Low gas prices, Low CO_2 prices	"Digging in Our Heels" High gas prices, Low CO_2 prices
Overview and Drivers of Technology R&D	Existing nuclear power R&D needs apply across all scenarios; the critical issue is the timing of these R&D needs: critical ones will be accelerated in "Double Whammy" for example			
Technology R&D Gaps: For each scenario, these represent the critical technology R&D needs in the area of existing nuclear power.	Establish an integrated spent fuel management system consisting of centralized interim storage, the Yucca Mountain repository, and long-term monitoring and management of the repository			
	Ensure the continued effectiveness and reliability of the operating fleet of nuclear plants			
Legend: Very critical; Critical; Important. Arrows indicate that the R&D need applies to *more than one scenario*	Reduce materials degradation, improve fuel reliability, develop advanced nondestructive evaluation techniques, improve equipment reliability, and upgrade instrumentation and control technology			
	Develop cost-effective, risk-informed asset management/business model			
	Improve management of low level waste and radioactive materials management			
	Identify role of technology (e.g., specialized training) in a workforce-constrained future			

Figure 3-7
EPRI Scenario and Technology Development Matrix for Existing Nuclear Power

Future Nuclear Power Capabilities

Overview

Nuclear energy in the U.S. is entering a renaissance. With strong interest and support for new plant construction, there is a sense of a bright future not only for nuclear energy's increasing role in U.S. electricity generation and reliability, but also in helping meet the challenges of 1) revolutionizing the transportation sector's dependence on foreign oil, 2) reducing the need to use natural gas for electric power generation and for the production of hydrogen for industrial applications, 3) fostering safe and proliferation-resistant use of nuclear energy throughout the world, and 4) achieving these in an environmentally responsible manner.

To forecast the U.S. nuclear technology needs, moderately aggressive planning assumptions were developed to guide the types and timing of the technology needed in seven major goals:

1. Ensure the continued effectiveness of the operating fleet of nuclear plants (see Section 3 on "Existing Nuclear Plants")
2. Establish an integrated spent fuel management system consisting of centralized interim storage, the Yucca Mountain repository, and, when necessary, a closed nuclear fuel cycle.
3. Build a new fleet of nuclear plants for electricity generation.
4. Produce hydrogen at large-scale for transportation and industry, and eventually for a hydrogen economy.
5. Apply nuclear systems to desalination and other process heat applications.
6. Greatly expand nuclear fuel resources for long term sustainability, commercializing advanced fuel cycles when market conditions demand them in the long term.
7. Strengthen the proliferation resistance and physical protection of closed nuclear fuel cycles both in the U.S. and internationally.

With these goals, a matrix of technology options to address each goal was developed with an assessment of the technology capabilities and challenges of each option. From this matrix, a technology development agenda was derived, with timing and cost estimates. Finally, current nuclear R&D programs were reviewed in relation to this assessment, and three areas were identified for action:

1. **Significant light water reactor research is needed.** Many significant needs exist for the current fleet and the new fleet, especially in areas of age-related materials degradation, fuel reliability, equipment reliability and obsolescence, plant security, cyber security, and low-level waste minimization. Additional needs include developing a new generation of LWR fuel with much higher burn up will better utilize uranium resources, improving operating flexibility, and significantly reducing spent fuel accumulations, which results in additional improvements in nuclear energy economics. A number of these are mid-term R&D needs with considerable impact, if accelerated.

2. **Nuclear energy's role in a future hydrogen economy can begin now.** An essential consideration in reducing dependence on foreign sources of oil and natural gas is found in the fact that hydrogen is necessary today in upgrading heating oil and gasoline, and in making ammonia for fertilizers. In fact, making hydrogen today consumes 5 percent of all natural gas in the U.S., and demand for hydrogen is growing rapidly. This situation can be improved via a nuclear system with hydrogen production capability as soon as it can be developed. In the mid-term, nuclear-produced hydrogen can be used to exploit heavy crude from large reserves in Canada and Venezuela. In the long-term, many believe that a hydrogen economy is essential for revolutionizing transportation, in which case the demand for competitive and environmentally responsible hydrogen will greatly increase. A large-scale, economical nuclear source would hasten that future.

3. **A proliferation-resistant closed fuel cycle for the U.S. should be ready for deployment by mid-century.** Establishing a closed fuel cycle with the demonstrated ability to handle much more nuclear waste will bring added confidence in a stable fuel supply and long term spent fuel management in the U.S. in support of greatly expanding the use of nuclear energy. It will also bring the potential for establishing a nuclear fuel lease/take-back regime internationally. This would reduce the number of countries that need to develop enrichment and reprocessing technology. Importantly, various advanced fuel cycle technology options provide the ability to supply sufficient nuclear fuel in the future to ensure long term energy and environmental sustainability for the U.S. and globally.

   Necessary technologies include cost-effective and proliferation resistant reprocessing to separate and manage wastes, and alternate reactor concepts (e.g., fast reactors) to generate electricity as they generate additional fuel and burn the long-lived minor actinides (i.e., heavy metal elements with atomic number 89 and 91) and other constituents that are recycled. These are both critical to assuring an adequate and economic supply of fuel, reducing the spent fuel backlog, and increasing the effective capacity of Yucca Mountain many-fold in the long term. While the technology challenges and market uncertainties are many, large-scale deployment of a closed fuel cycle could begin by mid-century.

A New Paradigm on Nuclear R&D

In July 2004, the Idaho National Laboratory undertook a step toward forging a consensus on the future direction of nuclear energy when it assembled a "Decision-Makers Forum" in Washington DC. That forum attracted a broad spectrum of key stakeholders in the nuclear technology enterprise. Using the results of this forum as a starting point, EPRI, technically supported by the Idaho National Laboratory (INL), developed an assessment of the nuclear systems R&D needed in the United States over the next half century. The assessment is founded on the assumption that nuclear energy will be challenged to expand dramatically in the world over the coming decades. A series of strategic planning sessions was held to map out a common set of high-level goals and time-based planning assumptions for nuclear energy, and to then identify the R&D needed to prepare for deployment consistent with those assumptions. Following this, R&D challenges were identified. Finally, an assessment of current nuclear R&D programs was made to identify opportunities for action.

The purpose of this consensus strategy is to develop an aggressive, success-oriented, yet credible and defensible R&D strategy for nuclear energy in the U.S. over the next 50+ years. The long time horizon is necessary to include the development of a closed fuel cycle.

Guiding Principles and Planning Assumptions

Three guiding principles were used to develop the consensus R&D strategy:

- Strive for a moderately aggressive yet credible technology portfolio
- Understand the importance of market forces to long-term planning. Each future Administration and Congress will make Federal investments in nuclear R&D only to the extent necessary to achieve national goals. However, the Federal government values the private sector's participation in that investment, and ultimately in its deployment. Thus, long-term market demand is a key factor in long-term nuclear energy investments and deployment.
- Align the technology portfolio with evolving nuclear energy policies and priorities. Widely divergent views on nuclear energy policy exist in the U.S. Yet a surprising consensus exists on basic priorities for technology development, as shown by a review of five key government and independent studies on the future of nuclear energy.

The process was to establish a high level set of success-oriented planning assumptions for 2015, 2030, and 2050, covering for example reactor technologies, fuel cycle technologies, spent fuel management, and infrastructure needs. These planning assumptions were then weighed against the three guiding principles above, in terms of broad national energy, economic, safety, and environmental goals, considering achievability, timing, and sequencing.

The planning assumptions proposed below are intentionally challenging, but also realistic and achievable. The predicted rapid growth is enabled by competitive economics, but is also accelerated in response to the growing societal demand to reduce the environments impacts of fossil fuels, including the risk of global climate change (by imposing limits on CO_2), which will increase demands for low- or zero-emitting sources. All three categories of low or zero-emitting technologies – nuclear energy, renewable energy, and fossil energy with carbon capture and sequestration – will face formidable challenges. Specific planning assumptions are summarized below:

Currently Operating Nuclear Plants:

- All existing plants remain operational in 2015, and all have applied for and have been granted a 20-year life extension. Despite continued high safety performance and record-setting reliability, materials aging and equipment obsolescence have moderated their former profitability. Continued high performance is maintained in part by strategic, safety-focused plant management, and in part by new technology solutions (e.g., advanced monitoring and repair techniques, improved fuel performance, remedial coolant chemistry, greater reliance on advanced materials and digital controls).

- In the 2020-2030 timeframe, some plants are granted an additional 20-year life extension (i.e., to 80 years). Advanced fuel designs with higher burn up limits enable longer fuel cycles, significantly increase fuel economy, and significantly reduce the rate of spent fuel generation.

New Plants for Electricity Generation:

- Six to twelve new nuclear plants are in commercial operation by 2015, with many more under construction. Thirty GWe of new nuclear electric generating capacity is on line or under construction by 2020. A cumulative total of 100 GWe of new nuclear capacity has been added by 2030. By 2050, nuclear energy is providing 35 percent of U.S. electricity generation by adding a cumulative total of about 400 GWe of new nuclear capacity. This number includes electricity generation from all reactor types. It also includes replacement power for a large segment of the current fleet of reactors, most of which have been retired or are close to retirement by 2050. This build-rate severely challenges the U.S. industrial infrastructure.

New Plants for Process Heat:

- Based on a prototype Very High Temperature Reactor (VHTR) built and operating by 2020, about twelve VHTRs are in commercial operation by 2030, with about twelve more are under construction. VHTRs are assumed to be commercially successful at 600 MWth per module (nominally four modules per plant), and with an outlet temperature around 850-900°C (1560-1650°F). The VHTRs are initially dedicated to producing hydrogen for commercial and industrial use, focused primarily on rapidly expanding hydrogen demand by the oil, gas and chemical industries. They expand to a fleet of roughly 200 by 2050, still focused primarily on industrial applications, but also serving a growing market for hydrogen to power fuel cells in hybrid and plug-in hybrid vehicles. U.S.-built commercial VHTRs are also serving hydrogen demand for U.S. companies at some petrochemical facilities operating overseas.
- Commercial versions of the VHTR, without hydrogen production equipment, also begin to serve process heat needs in the petrochemical and other industries. High value-added applications above 800°C (1470°F) are found in recovery of petroleum from oil shale and tar sands, coal gasification, and various petrochemical processes (e.g., ethylene and styrene).
- Nuclear energy begins to assume a significant role, starting in the 2020 timeframe, in support of the desalination mission for arid coastal regions of the U.S. with acute shortages of potable water. Some 16 trillion additional gallons per year will be required in the U.S. by 2020 for municipal and light industrial uses. This is equivalent to one quarter of the combined outflow from the Great Lakes. If desalination is viable with nuclear energy, it will likely be accomplished by equipment designed for new light water reactors, or by new reactors dedicated to desalination as are being pursued in other countries.

Spent Fuel Management and Expanding Nuclear Fuel Resources:

- Licensing of a spent fuel repository at Yucca Mountain Nevada is completed by 2015, with construction and waste acceptance into the repository and into nearby above-ground storage underway by that date. Interim storage away from reactor sites is also established at two other locations in the U.S., one east and one west of the Mississippi River.

- With a rapidly expanding nuclear energy industry and a growing inventory of spent fuel, an integrated spent fuel management plan for the U.S. emerges by 2015 that obtains bipartisan support for implementation. Key elements of the plan include expansion of the capacity of the Yucca Mountain repository, and a decision to maintain continued monitoring of the repository well in excess of 50 years (e.g., 300 years) prior to closure. The plan also includes a commitment to begin reprocessing spent fuel in a demonstration plant by about 2030, based on an active R&D program aimed at identifying cost-effective and proliferation-resistant means to recover usable reactor fuel. These technologies will also demonstrate the reduction of radiotoxicity and heat output of spent fuel, and the potential to greatly extend repository capacity. The reprocessing plan is integrated with both reactor technology and repository strategies, and offers a least-cost path for safe, long-term management of spent nuclear fuel.
- The reactor technology part of this integrated strategy develops means (e.g., fast reactors) to recycle light water reactor spent fuel in order to burn minor actinides as well as produce electricity, and later to breed additional fuel. Following a demonstration plant, built and operated with government funding in 2035, new fast reactors are deployed commercially, with government subsidy as needed for the waste burning mission. In the long term, the price of uranium increases to a level that supports breeding.

R&D Technology Matrix

A matrix was created to detail the specific technology agendas and programs. Goal areas were mapped against specific technology options, missions and capabilities. Estimates were made for when each capability is needed, how many years are needed to develop, license, and demonstrate each, and from these estimates, when R&D must start or ramp up. Key R&D needs for each technical capability were identified, along with specific challenges that needed to be addressed. Next, the matrix was used to compare the relative R&D challenges, and to consider the likelihood of success. The R&D matrix is summarized in Table 3-3.

Conclusions

- The strategy for nuclear energy development and implementation in the U.S. requires a consensus of industry and government.
- The overall strategy should be determined by a combination of market needs and long term nationally established energy goals for energy security, national security, and environmental quality.
- The priorities in the consensus nuclear energy strategy should address near-term, medium-term, and long term priorities. R&D needs to proceed now on all fronts, but priorities for implementation and deployment are as follows:
  - Near term goals include license renewal for the current fleet, and licensing and deployment of new, standardized ALWRs within the next decade. Near-term deployment of ALWRs will require demonstration of a workable licensing process, and completion of first-of-a-kind engineering for at least two standardized designs.

Table 3-3
R&D Technology Matrix for Nuclear Energy Development

Goal	Technology Option	Technical Capability
1. Ensure the continued effectiveness of the operating fleet of nuclear plants	Current LWRs	1A. Managing age-related degradation
		1B. Equipment reliability and system obsolescence
		1C. Power uprates
		1D. Plant security
		1E. Grid reliability
		1F. Radiation protection
		1G. Fuel reliability
		1H. New generation LWR fuel
2. Establish an integrated spent fuel management system consisting of centralized interim storage, the Yucca Mountain repository, and, when necessary, a closed nuclear fuel cycle	Interim Storage	2A. Acceptance criteria for transportation of spent high burn-up (HBU) fuel
	Yucca Mountain repository	2B. Transportation and storage of multi-purpose canisters
	Economic closed nuclear fuel cycle	2C. Proliferation-resistant reprocessing
		2D. Reactors that can burn minor actinides
3. Build a new fleet of nuclear plants for electricity generation	ALWRs	3A. Demonstration licensing process
		3B. Reduce capital costs (first-of-a-kind engineering, FOAKE)
		3C. Reduce construction time
		3D. Address shortfall in infrastructure
		3E. Reduce operating costs
4. Produce hydrogen at large scale for transportation and industry, and eventually for a hydrogen economy	LWRs	4A. Conventional electrolysis
	Commercialized VHTR – H2 only	4B. High temperature electrolysis (HTE)
		4C. Sulfur-iodine (S-I) or other chemical processes
	VHTR – cogen	4D. Cogeneration with 4B or 4C
	VHTR – all	4E. Codes and Standards development
5. Apply nuclear systems to desalination or other process heat applications	ALWRs (low T)	5A. Desalination, wood pulp, urea
	VHTR (high T)	5B. Petrochemical, coal gasification, iron reduction
6. Expand nuclear fuel resources for long term sustainability	Alternate fuel cycles and reactor concepts	6A. Closed fuel cycle with breeding (e.g., fast reactors)
7. Strengthen the proliferation-resistance and physical protection technologies of closed nuclear fuel cycles., both in the U.S. and internationally	Institutional needs	7A. Real-time materials accountability
		7B. Proliferation issues and policies
		7C. Framework for int'l fuel supply/take-back regime
	Reprocessing	7D. Closed fuel cycle with supply/take-back
		7E. Assessment methodologies and technology
		7F. Physical protection technology

To enable the resurgence of nuclear energy, the near term elements of an integrated spent fuel management plan must proceed. These near term elements include completion of the repository at Yucca Mountain, deployment of multi-purpose canisters approved by the NRC, implementation of an effective spent fuel transportation system, and provision for centralized interim storage

– Medium-term goals include development of a high temperature commercial VHTR capable of generating hydrogen and electricity at competitive costs, for initial use by the petroleum and chemical industries. Deployment will require concept development, defining end-user requirements and interfaces, engineering, resolution of design and licensing issues and prototype demonstration

– Long-term goals include development of new closed fuel cycle technologies supporting an integrated, cost-effective spent fuel management plan. Key elements of the plan include expansion of the capacity of the Yucca Mountain repository, and a decision to maintain continued monitoring of the repository well in excess of 50 years prior to closure. The plan also includes provisions for centralized interim storage of spent fuel, and a commitment to begin reprocessing spent fuel in a demonstration plant by about 2030, based on an active R&D program aimed at identifying more cost-effective and proliferation-resistant means to recover usable reactor fuel. It also includes development of safe and cost-effective fast-spectrum reactor technology for “burning” the long-lived actinides in spent fuel, and “recycling” the usable uranium and plutonium recovered from spent fuel. These capabilities, along with other advanced fuel cycle options, should be used to achieve long-term energy supply sustainability – long after fossil fuel supplies are exhausted.

- A strategy for rebuilding the nuclear industrial infrastructure in the U.S. is necessary. Currently, major equipment must be procured offshore. Long term energy security requires that the U.S. industry have the capability to supply and support U.S. energy producers, and better integrate energy supplier and end-user needs. These infrastructure needs include large numbers of new skilled construction workers, engineers, nuclear plant operators and other key personnel needed for construction, operation and maintenance of new facilities.

Key R&D Topics

Figure 3-8 summarizes the critical R&D needs in the area of future nuclear power capabilities. These R&D needs are also listed below:

- Demonstrate licensing process and reliability; reduce capital and operating costs, and reduce construction time
- Expand nuclear fuel resources for long term sustainability
- Develop advanced nuclear generation options (e.g., producing hydrogen)
- Develop and assist in demonstration of closed nuclear fuel cycle
- Define linkage between nuclear power and electric transportation from an energy security and environmental perspective
- Apply nuclear systems to desalination or other process heat applications

Scenario	**"Biting the Bullet"** High CO_2 prices, Low gas prices	**"Double Whammy"** High CO_2 prices, High gas prices	**"Supply to the Rescue"** Low gas prices, Low CO_2 prices	**"Digging in Our Heels"** High gas prices, Low CO_2 prices
Overview and drivers of technology R&D	The R&D needs relevant to developing future nuclear power capabilities apply across all scenarios; the critical issue is the timing of these R&D needs: critical ones will be accelerated in "Double Whammy" for example			
Technology R&D Gaps: For each scenario, these represent the critical technology R&D needs in the area of future nuclear power capabilities.	Build a new fleet of nuclear plants for electricity generations by demonstrating licensing process, reliability; and reducing capital, operating costs, and construction time			
	Address technical issues to enable cost-effective production of hydrogen at large scale for use by the transportation and industry sectors			
	Apply nuclear systems to desalination or other process heat applications			
	Expand nuclear fuel resources for long-term sustainability			
	Strengthen the proliferation resistance and physical protection technologies of closed nuclear fuel cycles.			
	Define the linkage between nuclear power and electric transportation from an energy security and environmental value perspective.			

Legend:
Very critical
Critical
Important

Arrows indicate that the R&D need applies to *more than one scenario*

Figure 3-8
EPRI Scenario and Technology Development Matrix for Future Nuclear Power Capabilities

Renewable Resources

Overview

As fossil fuel prices rise and CO_2 restrictions increase, utilities will benefit from adding renewable energy (RE) sources to the generation mix. Because RE sources such as wind and solar are virtually inexhaustible and involve no fuel costs, their use can offset high natural gas prices. And, most RE sources produce pollution-free energy. For example, wind turbines, photovoltaic cells, and hydroelectric plants do not emit greenhouse gases of any kind. Because RE resources such as wind and hydroelectric do not create solid waste byproducts that require disposal, they reduce a range of other environmental impacts as well.

Utilities are increasingly pressed to consider RE because of federal and state mandates for renewable portfolio standards (RPS). Figure 3-9 illustrates how much more renewable energy must be in place by 2017 to support existing RPS requirements. In addition to meeting regulatory requirements, adoption will create opportunities to sell RE-based power at premium prices to meet increasing consumer demand for "green" power.

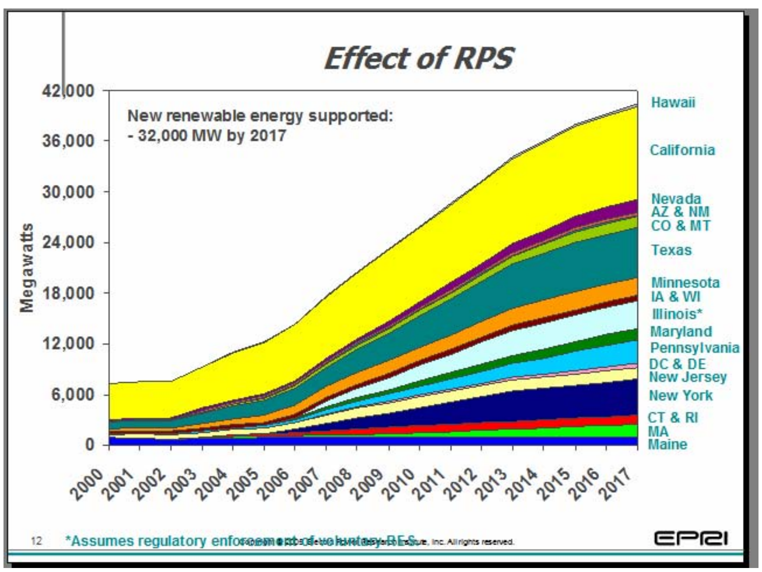

Figure 3-9
32,000 MW of renewable generation are required throughout the United States by 2017 to meet renewable portfolio standards (RPS) requirements

RE offers other benefits as well. By incorporating RE sources into the generation portfolio, utilities can better manage risks associated with fossil fuel price fluctuations. In addition, RE is well suited to certain applications. Technologies such as biomass and geothermal are dispatchable, making them valuable generation assets, while the output of non-dispatchable technologies such as photovoltaics can correspond well with summer afternoon load peaks. And because RE technology can be built in small-capacity increments that are proportional to load patterns and needs, individual regions can use locally available fuel sources to become more energy self-sufficient and sustainable.

Despite these benefits, obstacles stand in the way of widespread RE adoption. Historically, RE facilities have been more expensive to operate than fossil-fuel-fired and nuclear power plants, and generally require more equipment to create the same amount of energy. For example, thousands of windmills spread over several hundreds of acres are needed to equal the output of a single coal-fired plant. As a result, RE plants are difficult to scale. And, without advanced storage technologies that enable power to be stored when RE resource availability peaks, the intermittent nature of wind and solar power preclude a guaranteed supply of power. (More information about R&D opportunities for energy storage can be found in the section on electricity energy storage.)

However, all of the operating and economic issues associated with RE can be solved with adequate R&D. The following sections describe some of the most critical technology gaps for various kinds of RE sources.

Wind

Because of technological advances and manufacturing experience, wind is the fastest-growing large-scale power generation technology in the world. Wind is an abundant resource throughout the United States (see Figure 3-10), and if sufficient R&D occurs, wind can potentially generate as much as 5 percent of the nation's power needs by 2020.[6]

[6] "Putting Wind on the Grid," John Douglas, *EPRI Journal*, Spring 2006, pp. 6-15.

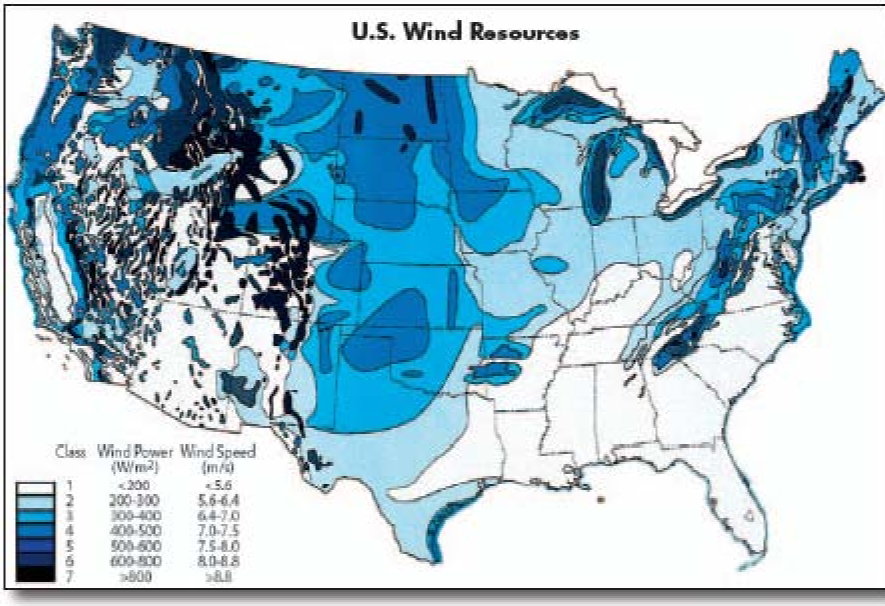

Figure 3-10
Wind Is an Abundant Resource in the United States, Especially in the West and Midwest

To reach this goal, the efficiency of wind generation systems must be improved so that more energy can be captured from the same amount of wind and the same number of windmills. Possible solutions include adding multicapacitors to windmill blades to adjust pitch for most efficient energy capture, increased rotor diameters, lighter weight designs, refinement of direct-drive generators, improved controls and power conversion technology, and higher towers. In addition, energy loss where wind power joins the grid reduces the overall system efficiency. Advanced power electronics that provide power output smoothing can improve the handshake with the grid and reduce these losses. In addition, energy storage and backup power generation resources at strategic locations on the grid can help alleviate some integration issues.

Advanced power electronics are also needed to solve a number of other technical issues associated with wind's intermittent nature. Short-term variations in wind can cause technical problems in matching the electrical characteristics of the wind turbine's power output to those of the local power network, and voltage sags resulting from a grid fault can trip a group of wind turbines offline unless the turbines are equipped with low-voltage ride-through capability. And because the induction generators used in most wind turbines absorb reactive power, an additional technical challenge is the limited ability of wind turbines to control reactive power. The use of power electronics with wind turbines can largely eliminate such problems, enabling efficient variable-speed operation, controlling reactive power, and providing better low-voltage ride-through capabilities when grid disturbances occur.

Intermittency presents planning problems as well. Utilities that invest in wind seek to generate wind power whenever possible, while still ensuring an adequate energy supply in case of reduced wind. If utilities can more accurately anticipate and plan for output variations, they can more reliably and economically integrate wind into a large utility system. Advanced wind forecasting capabilities are needed that enable output forecasting over hours and days, as well as the control technologies to help system operators dispatch resources in response to varying loads. In addition, long-term annual wind forecasting will enable utilities to estimate the annual contribution of wind resources, enabling better planning.

While wind power is extremely clean to produce, it is not without environmental impacts. Avian interaction with wind facilities is a central issue, as the deaths of various kinds of birds and bats have been reported in wind resource areas. The development of larger wind turbines can help mitigate this issue, because the turbine rotors will be higher than much of the avian habitat, and the slower rotor speeds will reduce the probability of striking animal life. Proper siting of wind equipment can help address this issue as well. R&D is required to design systems that pose less risk, and to develop siting plans that reduce avian interactions without affecting efficiency.

As ocean wind is both strong and predictable, offshore wind farms are an emerging technology that offer great promise. Because of backlash against installing wind farms where they are visible to the public, the development of deep-water wind farms situated below the horizon line is desirable. However, such remote siting presents unique challenges. Because the technologies must operate reliably and effectively in deep water, wind turbines should be ruggedized to withstand the marine environment of high waves, high winds, salt spray, and sometimes ice, and they must be more efficient to offset to the costs of offshore deployment. For water depths greater than about 30 meters, more complicated turbine foundation structures will be needed, using support cables, tripods, and truss towers for transitional water depths (30 m to 50 m) and floating foundations moored to the bottom by cables for deep water sites (50 m to 200 m). The costs of the cable connection for transmitting offshore wind energy to land are significant, and must be reduced to improve viability. Maintenance and repair also present special issues for offshore equipment. Because of the distance and complexity of travel to the site, equipment must not only be as robust as possible but provide accurate automatic diagnostic and communications capabilities to increase the efficiency of maintaining offshore facilities. Overall, R&D is required to develop, test, and commercialize solutions in all of these areas.

Solar Technologies

Solar energy, which uses the sun’s heat to create power, is an increasingly valuable resource. A future can be envisioned in which regions with significant amounts of sunlight can not only generate their own power but also export energy to other states. Figure 3-11 shows the distribution of solar radiation across the United States.

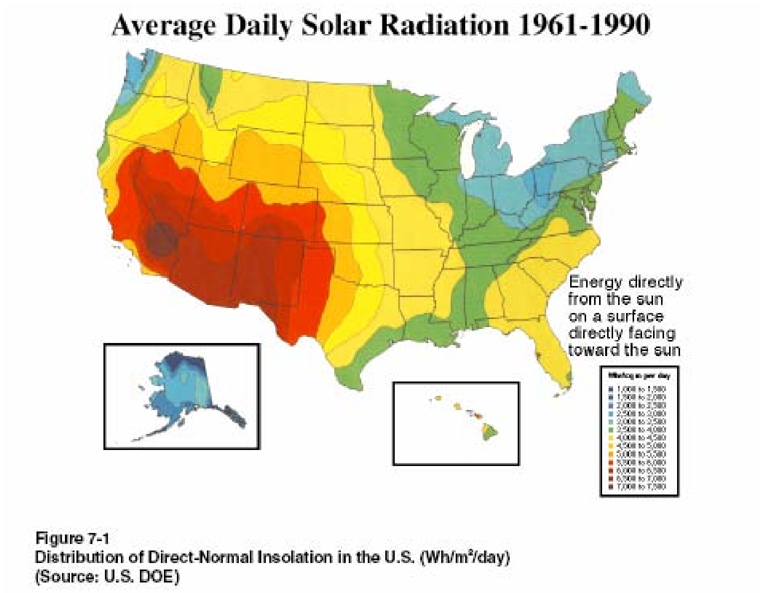

Figure 3-11
Significant Solar Radiation is Available Throughout the United States, Especially in the Southwest.

R&D requirements for the two main forms of solar power generation – solar photovoltaic and solar thermal – are described in the following sections.

Solar Photovoltaic. Solar photovoltaic modules, also known as photovoltaics (PVs), are solid-state semiconductor devices that convert sunlight into direct-current electricity. PVs have no moving parts, no fluids, no noise, and no emissions of any kind. They are ideal for a broad range of small-scale, on-site applications, as well as many remote applications. New PV technologies and policies that encourage distributed generators to interconnect to the grid will make PVs increasingly competitive, practical, and attractive.

Based on the experience of existing PV facilities, R&D is needed to improve efficiency and operations in the following areas:

- **Loss reduction.** Currently, a PV plant’s alternating current (AC) output is approximately 33 percent less than the sum of the direct current (DC) ratings of the PV modules themselves. Derating factors for PV power include imperfect use of the array’s land area (packing-factor loss), losses resulting from field-wiring resistance and module-mismatch (in which no two modules have precisely the same current-voltage characteristics), and DC-AC inverter efficiencies of less than 100 percent. R&D is needed to devise cost-effective solution to address these losses and improve efficiency.
- **Inverter reliability.** Repair and replacement of the DC-AC inverters used in PV plants is a significant O&M expense. R&D is needed to design and develop more reliable inverters for this application.

- **Interconnection and distribution improvements.** Issues related to the safety and power-quality effect of connecting PV to distribution feeders include islanding protection, fault contributions, and voltage regulation. R&D is needed to design a compatible interface that addresses these safety, reliability, and quality issues.

R&D is also needed to increase efficiency and reduce costs of the PV cells themselves. While today's crystalline silicon cells are the most efficient technologies to date, their manufacturing process remains relatively expensive and difficult to automate. Near-term improvements in crystalline cell manufacturing techniques to speed production and reduce materials consumption are needed to reduce costs and further adoption.

Current research into new PV materials shows promise, especially the use of various processes to deposit very thin films of amorphous silicon and other novel semiconductors on a low-cost substrate, such as plastic, glass, or metal foil. These "thin-film" cells offer several advantages over crystalline silicon cells, as they use considerably less raw material, and their manufacturing techniques are well suited for mass production. However, further R&D is required to improve the efficiencies of thin-film cells to match or exceed the efficiency of crystalline cells.

One potential benefit of thin-film PV's form factor is that it can be manufactured as flexible lightweight sheets or rolls, and incorporated into building materials such as roofing, window glass, or facades. Such PV systems – where building materials contribute to meeting the structure's energy demand – are termed building-integrated PV (BIPV). A building designed for BIPV from the start can be constructed so that its architecture, placement, landscaping, and physical plant optimize its solar energy capture and efficiency. However, further R&D is required to cost-effectively incorporate thin-film PV into building materials and support these structures' integration with the power system.

In the long term, further research is needed to develop innovative new technologies known collectively as "third-generation photovoltaics." The most promising of these is the multi-junction cell, which can already be found in some of today's commercial amorphous silicon modules. In a multi-junction cell, a device contains two or more working junctions stacked on top of each other so that the sunlight reaches the lower junctions after being filtered through the upper ones. This structure can deliver higher conversion efficiency by allowing the high-energy photons of the solar spectrum to be harvested separately from the lower-energy ones. In theory, multi-junction PV devices may be up to 86 percent more efficient than traditional PVs at converting sunlight to DC power. R&D is required to design, test, and commercialize multi-junction PV technologies.

Solar Thermal. Solar thermal systems use heat captured from the sun to directly or indirectly operate a turbine. The three kinds of solar thermal technologies are the following:

- **Parabolic troughs.** This technology uses a collector field of single-axis tracking, parabolic-trough solar collectors to focus the sun's direct-beam radiation onto a collector for use in generating superheated steam. This is the only solar thermal technology that has achieved commercial operation at significant scale. R&D is needed to identify cost-effective methods of increasing both overall plant size (including thermal storage) and total collector area.

- **Solar central receivers.** Solar central receiver plants use hundreds to thousands of sun-tracking mirrors called heliostats to focus concentrated solar radiation on a tower-mounted heat exchanger (receiver). An early demonstration of this technology shows that it can be a dispatchable resource in the generating mix. However, unresolved issues include limitations on useful energy collection from long thermal time restraints; problems with system startup in high winds, and a lack of useful information about the lifetime and maintenance requirements. R&D is needed to expand the body of data available about solar central receivers and to address these identified concerns.
- **Dish-engine.** Dish-engine systems use a parabolic reflector to focus concentrated sunlight onto a fluid in a receiver tube at the focal point of the dish, which transfers heat to a small engine used to generate electricity. When the technology matures, dish-engine systems are expected to deliver higher efficiency, greater modularity, and more autonomous operation than parabolic trough or solar central receiver systems. However, significant R&D is needed to identify the most efficient and cost-effective designs for dish-engine systems, including a comprehensive evaluation of the potential of both Stirling and Brayton engines.

R&D is needed to further design, test, demonstrate, and commercialize solutions appropriate for various operating conditions for each of these three technologies.

Hydroelectric

Hydroelectric power is a proven technology, currently supplying 20 percent of world electricity. A major advantage of hydroelectric power over other RE sources such as solar and wind energy is that it is less intermittent and more predictable.

Although hydroelectric power is proven and cost-effective, R&D is needed to improve the operation of existing plants and ease the deployment of new facilities. One of the greatest factors hindering the deployment of hydroelectric power in the United States is concern about the environmental impact of damming rivers, which significantly changes watershed ecosystems. In addition, fish may be killed by turbines and other equipment. R&D is needed to design and commercialize "fish-friendly" turbines that operate efficiently while reducing impacts on aquatic life.

For hydroelectric plants that are already deployed, beneficial R&D includes efficiency improvements to extract more energy from existing facilities, such as through turbine and generator uprating and leakage control. In addition, better plant diagnostics are needed so that turbines and generators can be repaired in advance of failure, ensuring their full availability on high-demand days when they are needed most.

Hydroelectric power can be used in conjunction with other technologies to create pumped storage plants that do not require damming waterways. Power generated from a local, non-hydroelectric source is used to pump water from a catch basin to a higher elevation during low-cost off-peak hours, where it is released downhill to the reservoir as needed during high-cost peaking hours to provide additional power. The integration of wind and hydroelectric power for these systems is an intriguing possibility, as it increases the value of wind power by minimizing the problems associated with its intermittency. R&D is required to analyze the most effective designs for such systems, including effective pumping power sources for different sites, and to test and commercialize such systems.

Biomass

Biomass fuels, which are produced by living plant and animal matter, provide electric utilities and other electricity generators with dispatchable renewable power. Some biomass currently used as fuels consists of residues from processes that have other material value as well. For example, other markets for wood waste may include mulch for urban areas, bedding for livestock and poultry, feedstocks for materials such as particle board, and feedstocks for niche chemical and related products. As a result, biomass fuel pricing is highly sensitive to locale and the competitive pressures of local and regional economies. The use of biomass in generation is commercially available today, especially in cofiring generation with coal. However, the issues of biomass cost and availability must be addressed, and the process of gathering and concentrating the fuel in a single location is a primary consideration. To facilitate reliance on biomass fuels, R&D is needed to develop short-rotation crops such as switchgrass that can be competitively priced for use exclusively as fuel feedstocks.

In addition to direct firing or cofiring, a biomass fuel source can also be gasified with hot or warm gas clean-up for use as a generation fuel with combustion turbines in integrated gasification combined-cycle (IGCC) applications. Pressurized biomass gasification for power generation applied at a large scale (greater than 50 MW) can be competitive when compared to other low-cost renewable options. Through the use of more efficient gasification combined-cycle processes, a plant may produce power with 40 percent efficiency, compared to current combustion-based biomass efficiencies in the 26 to 30 percent range. In addition to combined-cycle power, commercial gasification plants could also produce clean syngas for use as a carbon-neutral feedstock for combined heat and power at industrial sites. However, R&D is needed to address significant technical issues associated with feeding biomass into a gasifier and with subsequent syngas cleanup. Reliable and cost-effective solutions to these issues must be demonstrated before commercialization of biomass gasification can proceed.

Biogas

Biogases are low-energy-content gases that result from the decomposition of organic matter. When sufficiently processed, biogas can serve as a fuel for power production. One source of biogas is landfills, which can contain significant amounts of methane. Because methane is a greenhouse gas with greater environmental impact per ton than carbon dioxide (CO_2), burning methane and releasing CO_2 actually produces fewer greenhouse emissions than continuing to allow the methane to enter the environment. Some estimates indicate that landfill gas alone could replace 0.5 percent of the conventional fuels for U.S. electricity generation while providing a climate change benefit equivalent to reducing electricity-sector CO_2 emissions by more than 5 percent. R&D is needed to identify cost-effective ways to purify biogas for use in firing applications, such as a membrane-based cleaning system suitable for operation in a remote location.

Biogas can also be generated through the anaerobic digestion of waste agricultural sources. Such an approach could generate even more fuel than landfills and solve the environmental problem of disposing of these waste products. R&D is needed to test possible solutions in this area.

Ocean Energy

Ocean energy relies on harnessing the environmental characteristics of the ocean to generate electric power.

- **Ocean tidal.** Ocean tides, which result from gravitational forces exerted by the moon and the sun, are strong and exceptionally predictable. In principle, the force of the tidal flow can be used to drive turbines. R&D is needed to design and test turbines as well as transmission lines for transporting tidal energy to shore. One promising idea is for offshore wind and ocean tidal structures to share a common platform and transmission system, reducing deployment and O&M costs.
- **Ocean wave.** Because ocean waves are consistent and sea states can be accurately predicted more than 48 hours in advance, harnessing wave energy can offer a possible energy source. A number of different device designs for extracting wave energy have been proposed, but preliminary R&D is required to further refine and test these designs.

For both kinds of ocean energy, R&D is required to develop power equipment that can withstand the marine environment for 30 to 40 years. Impacts on marine life and coast line must be considered as well.

Geothermal Energy

Electric power generation from geothermal steam reservoirs is a mature technology with a worldwide operating capacity of approximately 8,900 MW. The possibility to develop additional geothermal capacity exists. However, R&D is needed to improve drilling techniques to fully identify a site's potential and speed the exploration process. In addition, both existing and future geothermal generation will benefit from improved efficiency and reduced costs resulting from better technical performance, and improved materials and coatings that increase equipment's useful life.

Grid Integration Issues

Although RE sources offer environmental and economic benefits, the nature of the resources themselves and the equipment used to produce power from them can lead to system integration issues, as many renewable-driven generators cannot perform all the functions that are expected from traditional generation. And, because renewable energy is relatively new, planners and operators of bulk-power systems have limited experience to make changes that may be needed to integrate large-scale renewable power into the existing power grid.

R&D is needed to address the technical issues and associated cost issues related to the impacts of intermittency, ramping, fluctuating output, lack of control, and remote location on transmission scheduling, system dispatch, network stability, load following, and load balancing.

Conclusions

While the technologies for widespread RE adoption are not yet fully in place, stewarding their development will diversify the energy supply, improve air quality, enhance power management, and develop a range of new market opportunities while reducing national dependence on fossil fuel and increasing sustainability. R&D requirements for renewable energy are aligned with the four economic scenarios as follows:

- **The "Biting the Bullet" Scenario.** When CO_2 costs are high, renewables will be added to the generation mix primarily to reduce overall emissions. To ease RE deployment, emphasis will be placed on low-cost energy options, such as wind and biomass cofiring. Solutions for energy storage, integrating wind and hydroelectric energy, and reducing the costs of biomass fuel collection and transportation will boost efficiency, increasing the contribution of RE to total generation.
- **The "Digging in our Heels" Scenario.** In this scenario, the goal is to offset high natural gas costs by adding low-cost renewable energy options. The near-term emphasis in this scenario will be on options that are the first resource to be used or to dispatch, such as biomass gasification, small hydro, and wind.
- **The "Double Whammy" Scenario.** The greatest drive to adopt RE occurs when both natural gas and CO_2 costs are high. R&D is needed to improve the efficiencies and reduce the costs of all technologies, as utilities will benefit from considering any RE technology available in their regions to offset higher generation costs. Building-integrated energy systems, including the increased use of RE (especially thin-film solar PV) for individual buildings and communities, will become increasingly important as consumers seek long-term solutions for energy sustainability and cost reduction.
- **The "Supply to the Rescue" Scenario.** When natural gas is abundant and CO_2 costs are not an issue, RE is less important than in other scenarios. However, existing RPS requirements are likely to still exist, even if additional regulation is not in place. In this scenario, RE must be affordably deployed and offer additional benefits such as power quality improvements.

In all cases, R&D is needed to improve the performance, availability, and cost effectiveness of new and existing RE capacity, including the development of condition monitoring and predictive capabilities for all RE technologies. And, grid integration issues to reduce losses and minimize operating issues must be addressed as well. Figure 3-12 illustrates the greatest opportunities in each scenario, while Figure 3-13 illustrates the relative importance of each technology area to the scenarios. When these R&D goals are reached, RE's tremendous potential can be fully realized.

Key R&D Topics

Following is a list of the key R&D topics for the area of renewables resources:

- Develop renewable value proposition in generation mix (to include renewable portfolio standards and regulatory credits)
- Integrate renewables with energy storage, end-use efficiency, transportation, and transmission / distribution systems
- Demonstrate emerging technologies to obtain credible cost, reliability and performance metrics
- Improve operating efficiency of hydroelectric plants
- Develop credible wind energy forecasting tools

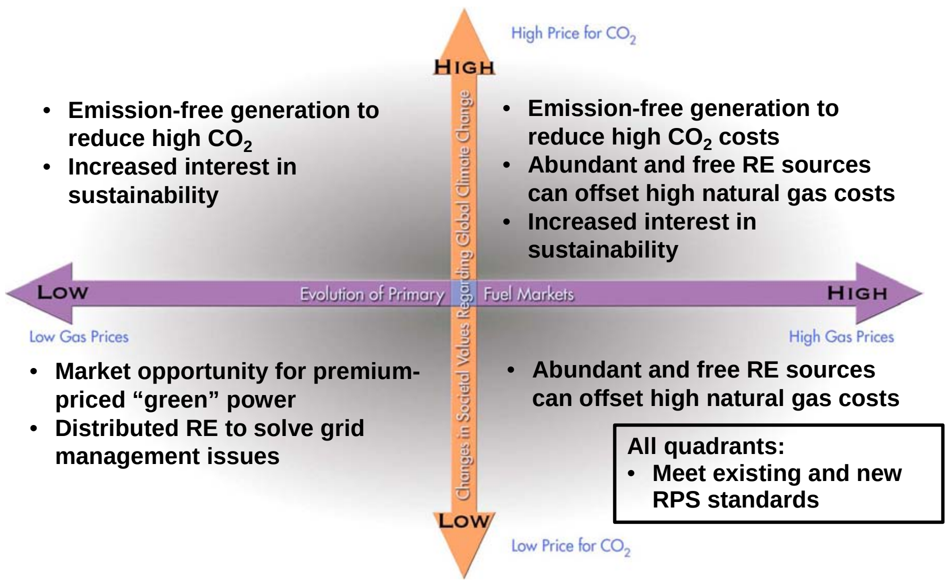

Figure 3-12
Opportunities in Each Scenario Drive Development in Renewables

Scenario	"Biting the Bullet" High CO_2 prices / Low gas prices	"Double Whammy" High CO_2 prices / High gas prices	"Supply to the Rescue" Low gas prices / Low CO_2 prices	"Digging in Our Heels" High gas prices / Low CO_2 prices
Overview and drivers of technology R&D	Environmental concerns in this scenario support faster development by regulation. Add RE to reduce CO_2 emissions in response to regulations.	Environmental concerns in this scenario will support faster development by markets. Add RE to reduce CO_2 emissions, sell into energy and ancillary service markets, and reduce pressure on gas demand and price.	Must compete with gas and other alternatives on price basis. Add RE if low-cost option to reduce cost, reduce risk of future gas price increases, and solve grid management issues.	Must compete with gas and other alternatives on price basis. Add low-cost RE options to reduce cost vs. gas.
Technology R&D Gaps: For each scenario, these represent the critical technology R&D needs in the area of renewable resources.	Develop renewable value proposition in gen mix → (very critical)	→ (very critical)	- - → (critical)	→ (very critical)
	Improve RE technologies to reduce costs and increase efficiency → (very critical)	→ (very critical)	- - → (critical)	→ (very critical)
Legend: Very critical → ; Critical - - → ; Important - - → (blue)	Integrate renewables and storage to improve efficiency and dispatchability → (very critical)	→ (very critical)	- - → (critical)	- - → (critical)
Arrows indicate that the R&D need applies to *more than one scenario*	Improve grid integration to reduce losses and improve RE management → (very critical)	→ (very critical)	- - → (critical)	→ (very critical)
	Integrate renewables and end-use efficiency improvements → (very critical)	→ (very critical)	- - → (critical)	- - → (critical)
	Enable better grid operation and power quality - - → (critical)	- - → (critical)	→ (very critical)	- - → (critical)

Figure 3-13
EPRI Scenario and Technology Development Matrix for Renewable Resources

Distributed Energy Resources

Overview

Perhaps no other technical area in this report covers a broader array of electric utility issues than distributed energy resources (DER). By definition, DER includes small generation or energy storage devices that can be located on the distribution system or at or near the end use consumer. Issues associated with this end use, such as building electric and thermal use patterns, affect DER system sizing. In addition to forming this link between power generation and end use, DER can provide potential system benefits due to elimination of the power delivery system between power production and consumption. On the other hand, it can work in concert with other equipment to actually help solve power grid problems, such as grid congestion. Yet, as discussed later in this section, DER overlaps with other technical areas as well. A plug-in hybrid vehicle is essentially a mobile DER, and small renewables resources, such as photovoltaic arrays or small wind generators, are also DER. Distributed resources are an important element in both alternating current (AC) microgrids and combined AC/direct current (DC) microgrid systems. Looking more long-term, DER can be a key part of an envisioned hydrogen-electric economy, in which production of hydrogen for the transportation sector is co-located with distributed generation at refueling stations.

Despite this broad reach, DER is not widely deployed today due to slowing interest in deregulation and rising natural gas prices (the fuel of choice for DER). According to the Energy Information Administration, at the end of 2003, an estimated 234 GW of DER capacity was installed in the U.S., with DER defined as generation of less than 60 MW in size. However, 81 percent of this capacity was comprised of small to medium reciprocating engines serving end-user needs primarily in emergency/standby applications. Moreover, only 13 percent (30 GW) of the total DER capacity was interconnected with the transmission and distribution (T&D) system and thus useable as a grid asset. This accounts for only 3 percent of the U.S. electric grid capability of 953 GW.[7]

DER could have a significant impact on the future of the T&D system and its design, including better utility asset utilization and less expensive system upgrades to meet new peak demands. Opportunities also are being explored for DER to be applied in joint utility/end-user applications – to meet both consumer end-use needs as well as utility grid support – and thereby to capture dual benefits. Because DER technologies can operate quietly and with few emissions, they may be relatively easier to site in metropolitan areas than central station plants, while avoiding expensive alternatives for upgrading T&D capacity. Future applications of DER may indeed serve the needs of T&D-constrained urban cities with challenging emissions regulations, such as Los Angeles, Houston, and Atlanta. This environmental benefit is particularly useful in the "Biting the Bullet" scenario where low natural gas prices enable DER to compete with other power generation options on price and emissions. However, much R&D remains to be performed to reduce the costs of DER technologies and improve equipment efficiency for end users, while facilitating applications in concert with the needs of the grid.

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[7] Dan Rastler. "Are Distributed Energy Resources Gaining Traction?" *Public Utilities Fortnightly*, February 2005, pp. 48-53.

The Hybrid DER Solution

The portfolio of DER generation technologies includes reciprocating internal combustion engines (500 kW-5 MW), small combustion turbines (5-50 MW), smaller microturbines (kW-scale), and various types of fuel cells, including phosphoric acid, proton exchange, molten carbonate, and solid oxide systems. Well-established technologies, such as reciprocating engines and combustion turbines, are making incremental improvements in cost, efficiency, and reliability, and are now able to cost-effectively achieve single-digit NO_x emissions (a level that many new central station plants are now required to achieve). But to overcome cost and efficiency barriers to broad use of DER, one of the best candidate generation technologies today appears to be a hybrid DER cycle that includes the integrated combination of advanced fuel cell technology and a small microturbine with utilization of waste heat.

Envisioned as a modular, truck-transported package, this hybrid DER cycle would feature very low emissions. Designed to serve applications that require approximately 5-10 MW of power, its uses could include relief in T&D constrained areas. The package could be located at substations in non-attainment zones (where reducing emissions of nitrogen oxides (NO_x) and other pollutants is paramount), while relieving transmission congestion in the area. Another application leverages the rapid deployability of this option. To respond to rapid, unanticipated load growth in a particular area, this option – which can be deployed in a matter of months – would provide short-term relief while more permanent central station generation – which can require years to permit and construct – is installed. Such hybrid fuel cell systems may also include co-location and integration with large energy storage systems, such as the 1-MW/7-MWh sodium sulfur battery systems.

A third application for this hybrid DER cycle is large commercial/industrial end users that need a reasonably-priced option for highly reliable power on-site. This diversity of applications for this option points out a key aspect of the future of DER: the business model employed. Today, a fragmented industry comprised of small engineering firms and consulting companies install most DER systems. Yet in the future, a variety of business models are possible. In environmental based scenarios, public utility commissions may require regulated utilities to include DER assessments within their distribution planning efforts. Even in the absence of regulation, some non-regulated energy companies are likely to re-evaluate the potential business opportunities that DER poses if conditions warrant it. For example, lower natural gas prices (which fuels DER equipment), lower DER costs, and higher DER efficiency would certainly merit an analysis.

The Efficiency Challenge

In somewhat smaller commercial/industrial and even residential applications (e.g., hundreds of kW to a few kW), end users such as hotels, hospitals, and other facilities that have a need for process heating or cooling would benefit in the form of lifecycle energy cost savings. Integrating high efficiency fuel cells with large heating/cooling needs in a combined heat and power (CHP) arrangement is achievable, given a major R&D effort to reduce costs and improve efficiency. Micro-CHP/cooling systems are currently in the development and early deployment stage in Europe and Japan. Such future systems are envisioned to be part of a “Smart House.”

Systems with low-cost power electronics, interconnection, communications, and control components would be needed for this to be economically feasible. By maximizing overall thermal efficiency, integrated and packaged configurations could be more efficient than even the most efficient new central station plants, when energy and delivery losses are taken into account. This makes this type of DER especially attractive in the "Biting the Bullet" scenario where low natural gas prices enable DER to compete, and highly efficient DER reduces CO_2 emissions. This is consistent with the regulatory mandate in this scenario in which utilities are encouraged or incented to help deploy or enable a host of supply-side and demand-side energy efficiency options.

The efficiency advances needed are challenging. Efficiencies for existing internal combustion engines, microturbines, and fuel cells are approximately 40 percent, 30 percent, and 40-45 percent, respectively. The leader in this horse race, fuel cells, when combined in a hybrid DER cycle with a microturbine, promises efficiencies as high as 55 percent in the next few years. The goals of achieving efficiency of 60-70 percent with a capital cost of less than $800/kW would be attainable in ten years with an aggressive R&D program and market adoption initiative.[8]

A variety of fuel cell types should continue to be examined (e.g., phosphoric acid and proton exchange membrane based fuel cells). In the proton arena, the cost of platinum and the membrane are key drivers. Research needs include novel alloys with low platinum loadings, as well as increases in membrane life by a factor of ten to reduce lifecycle costs.

Distributed Storage

Opportunities for distributed storage technologies, either in stand-alone mode or in combination with distributed generation, are promising, but also hinge on R&D that significantly reduces costs. In stand-alone mode, distributed storage in the form of advanced batteries or capacitor banks for example, can be used in residential and small commercial applications to reduce end-user electricity bills, or in utility applications to manage grid assets and improve peak load management. By taking advantage of time-of-use metering, batteries can be charged overnight with off-peak electricity and discharged to reduce electricity purchased during relatively expensive on-peak periods. This form of demand response or energy management also improves consumer reliability. In addition to the cost reduction issue, this application needs to be examined in terms of various business models (e.g., who owns the batteries).

When used in combination with distributed generation, distributed storage can be used to reduce the overall capital cost of the package. If the storage capability is lower in cost per kW than the generation capability, this makes economic sense. This entails operating the generation device as a mini-baseload generator (which reduces wear and tear on the unit, compared to cycling its output up and down) and meeting the balance of fluctuating demand with the distributed storage system. For example, a hybrid fuel cell could be used in conjunction with an advanced battery in a non-attainment area to provide both baseload and peak power needs.

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[8] By comparison, the efficiency of a state-of-the-art central station, combined-cycle power plant with the newest H-class combustion turbines is about 60 percent (see Figure 3-3).

DER can also be used in conjunction with various other generating technology hybrids, flywheels, supercapacitors, and superconducting magnetic energy storage systems. Refer to Section 4 on energy storage for more information on some of these technologies.

Ties to Other Complementary Technologies

Photovoltaics, small wind turbines, and other renewables such as small biomass can be used in DER configurations. Because these types of DER do not burn natural gas, they overcome a key limitation of gas-fueled DER – the difficulty of competing with other power generation options when natural gas prices are high. Environmental benefits also accrue, due to avoiding combustion of fossil fuels. PV, for example, can be integrated with a small electric storage package with a common low-cost inverter to convert the DC power collected to the AC power needed by the end user. This dispatchable storage system would be of value to electric utilities trying too manage the system peak between 4-9 pm. This example highlights an R&D need that cuts across a range of distributed resources: the need to reduce the cost of these inverters – a crucial power conditioning need.

Advanced and novel DER concepts under development with accompanying further R&D needs include small Stirling engines (primarily for residential applications) and direct carbon conversion systems (electrochemical conversion of coal through a series of redox reactions).

Distributed generation and distributed storage can also be integrated with voltage stability equipment (such as power electronics-based devices) and a control system in an uninterruptible power supply "UPS substation" arrangement. In this block of integrated components, the control system would use the voltage stability equipment alone to help address a transient local voltage problem. During a relatively short power interruption, the voltage stabilization system and storage device would work together to solve the problem. In the event of a longer power interruption, the control system would energize the generator to provide the power needed. Not yet developed, this concept could first be demonstrated at the distribution level for a commercial/industrial consumer (e.g., a data center) that needs guaranteed 100 percent reliable power.

In another DER application related to the distribution system, DER is a key element in AC microgrids, in which a portion of the distribution system can become an adaptable "island." Similarly, DER supports a combined AC/DC system that could be constructed, for example, in a large commercial building. Refer to Section 6 on distribution for more information on this topic.

Plug-in hybrid vehicles can be considered to be mobile DER because of their ability to return energy to the grid. Here, the R&D need is the daunting task of properly interconnecting the large number of these vehicles that are likely to "plug-in." Development of a common energy storage platform that is suitable for both plug-in hybrid electric vehicles and stationery energy storage would be beneficial. Refer to Section 7 on electricity-based transportation for more information on this topic.

Distributed energy resources can also be an important part of a transition to a hydrogen-electric economy using fuel cells and biologically produced hydrogen to provide electricity in an efficient, environmentally-sound manner. Refer to Section 9 on this topic for more information.

Conclusions

The following actions are recommended to close the technological and policy gaps in the DER areas:

Cost and Performance. Continued R&D is needed to lower the total capital installed cost, improve reliability, reduce O&M costs, and enable fuel flexibility. Advances are needed to improve the cost and performance of energy storage technologies. Advances also are needed to develop improved integrated packages specifically to meet end-user market applications. For example, standardized energy solution packages are needed for CHP, back-up power, peak shaving, and UPS markets; research is needed to develop low-cost meters and a low-cost plug-and-play interconnection device for larger kVA DER options, especially for CHP and peak-shaving applications. Another key need is to address institutional and policy barriers that limit market adoption.

Power Delivery System Support. Economic tools and best practices are needed to help evaluate and justify the technical and economic feasibility of incorporating DER into the T&D planning process. But because today's grid never really was designed for DER (or active, demand-side management options as well), new grid designs that maximize the use and value of DER (and especially energy storage) need to be developed and implemented by electric utilities. This will require R&D to provide more robust and sophisticated communication protocols to enable control and dispatch of DER devices.

Energy Supply. Development is needed of advanced, hybrid DER systems that are low-cost, efficient, and capable of being quickly deployed; standardization of products and pre-certification of systems are needed to verify the reliability of DER technologies; and vendors need to develop DER options that have the flexibility to burn alternative fuels.

Planning. Utility rate structures, including standby charges, should be evaluated to determine if redesigned rates might provide win-win opportunities; and incentives should be explored to encourage efficient DER-CHP/cooling systems. Market-based regional planning that recognizes the diversity of DER options is also needed to enable a more flexible and dynamic grid. Such regional market-based integrated resource planning should be explored to enable the optimization of new supply-side resources, renewables, DER, T&D investments, energy efficiency, and the environmental trade-offs.

Mapping DER to the Scenarios

Because distributed generation devices are almost exclusively fueled with natural gas, natural gas prices have a dramatic effect on the cost-effectiveness of DER projects. One way to look at DER cost effectiveness involves the "spark spread." This is defined as the difference between the price to produce electricity from natural gas fueled DER and the price of retail electricity. As natural gas rates rise, the spark spread narrows, and DER becomes less competitive. This means that the conditions currently experienced (some of which are indicative of the "Digging in our Heels" scenario) would not be advantageous for DER, and this is in fact what analysts are seeing today (see Figures 3-14 and 3-15).

Conversely, low natural gas prices widen the spark spread and increase the cost-competitiveness of DER, compared to other power generation options. In the "Supply to the Rescue," scenario all electric DER (i.e., not combined with district heating or cooling) is a favorable option, because it is likely to be able to compete effectively on a cost basis with other generation options. Moving up to the "Biting the Bullet" scenario adds the environmental dimension. In this scenario, DER in a combined heat and power arrangement that maximizes efficiency and reduces emissions is likely to be a viable option. An all-electric DER device is likely to be only marginally attractive in this scenario.

In the "Double Whammy" scenario, only very high efficiency CHP arrangements, or renewable-based DER, have a chance to overcome the high natural gas cost barrier.

Key R&D Topics

Following is a list of the key R&D topics for the area of distribution energy resources:

- Reduce cost and increase efficiency of fuel cell hybrid systems (to include combined heat and power systems)
- Define, develop and demonstrate plug-in hybrid fuel cell vehicles as a mobile distributed energy resource
- Reduce cost and integrate distributed energy resource systems with distributed storage (e.g., battery/super-capacitors)
- Reduce cost of renewable distributed energy resource systems (e.g., photo voltaic systems)
- Develop and demonstrate distributed uninterruptible power supply (UPS) substation
- Integrate DER with flexible electric distribution topologies (including microgrids and the IntelliGrid) to improve power reliability and quality; and integrate with the energy service portal

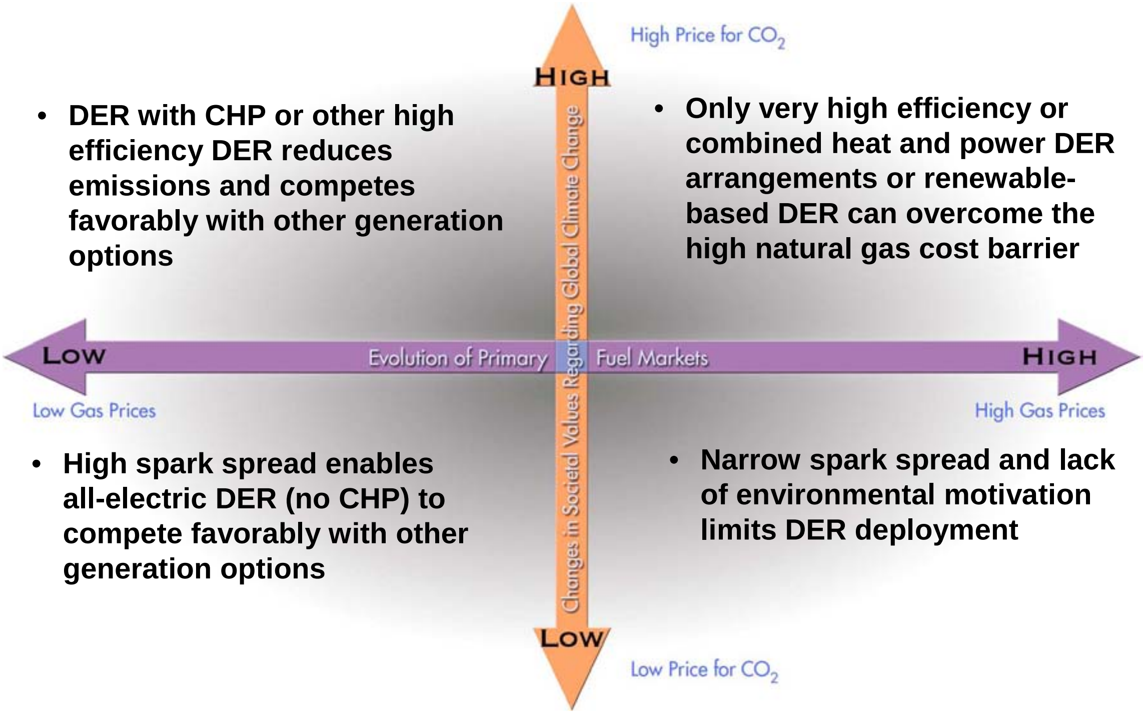

Figure 3-14
Opportunities for Distributed Energy Resources in Various Scenarios

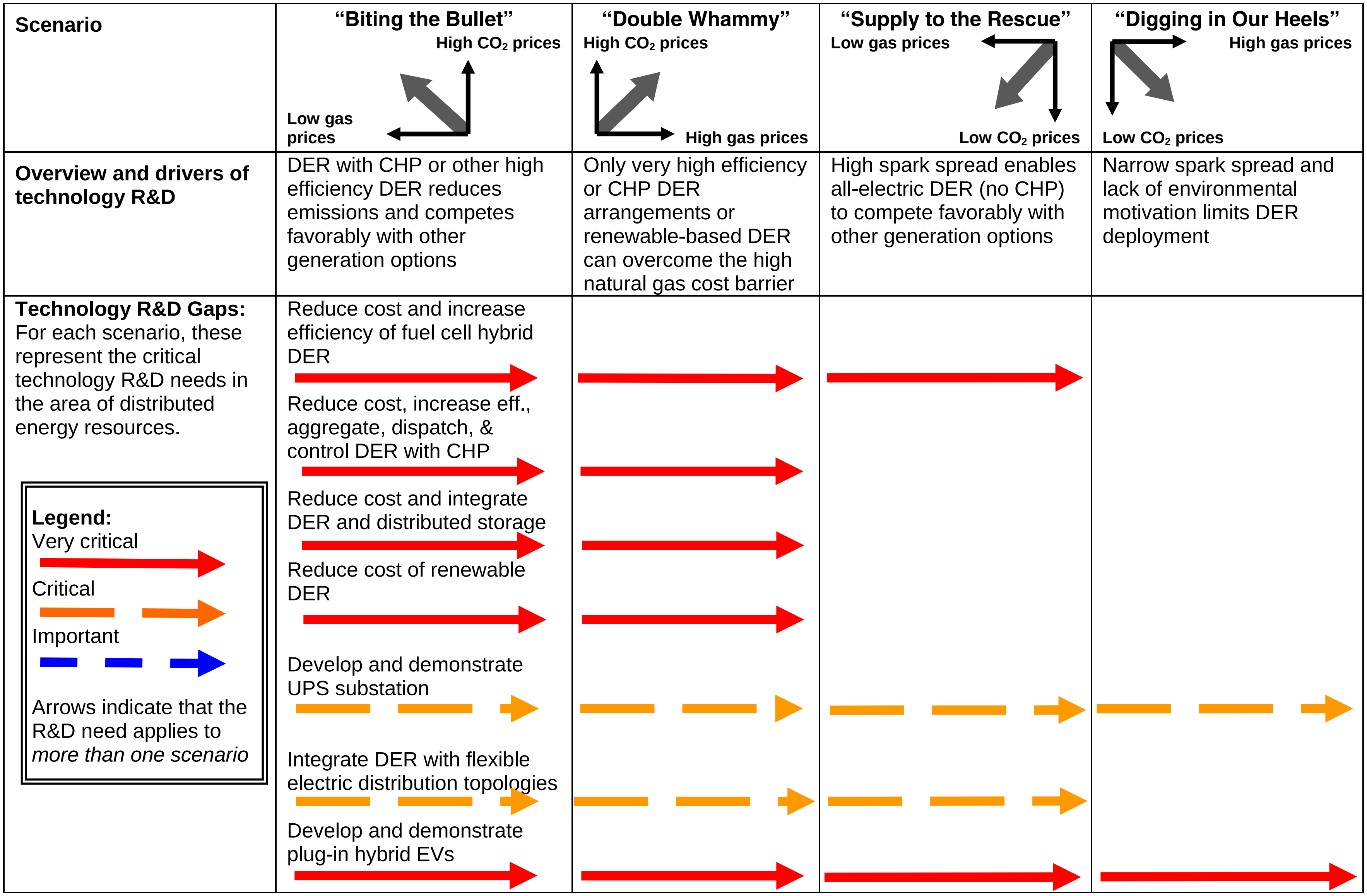

Figure 3-15
EPRI Scenario and Technology Development Matrix for Distributed Energy Resources

4
ELECTRIC ENERGY STORAGE

Electric energy storage provides a range of benefits to utilities, consumers, and society. Unlike many technologies covered in this report, which are advantageous in a single part of the electric power supply chain, electric energy storage cuts across the entire supply chain (i.e., power generation, power delivery, and end use). At the same time, electric energy storage provides various environmental benefits, including reduced emissions of CO_2 and other pollutants depending upon the plant used to charge the energy storage plant. And in most cases, electric energy storage increases the value of the technologies it complements (e.g., storage improves the value of renewables by addressing issues of intermittent generation, storage enhances distributed generation cost effectiveness, and energy storage improves electricity-based transportation). What's more, electric energy storage covers a broad size range – from small-scale, single consumer uses at the kW scale, to central station applications at the 1000 MW scale. This versatility means that further R&D and deployment of energy storage technology is highly likely to be a "win-win" proposition for all involved stakeholders.

Overview

Energy storage overcomes the only major limitation in electricity's flexible value; namely, energy storage devices provide a buffer (sometimes called a shock absorber) function that mitigates the requirement to generate and deliver electric energy in the instant that the consumer demands it. Yet despite the advantages of energy storage technologies, today in the U.S., energy storage plants provide only about 2.5 percent of total U.S. electricity capacity, nearly all of it from pumped-hydro installations used for load shifting, frequency control, and spinning reserve. In sharp contrast to the U.S. situation, some 10 percent of all electric capacity in Europe is cycled through a storage facility of some kind before delivery to the consumer, while in Japan energy storage plants encompass about 15 percent of total electricity generation capacity.

These country-to-country differences reflect, in part, dissimilar economic conditions. Current bulk storage technologies such as pumped hydro plants involve large physical scale and high costs that have generally removed them from new plant consideration in the U.S. In most cases where bulk energy storage would be useful in this country, historically, it has simply been cheaper to build new peaking combustion turbines to provide reserve generating capacity that can be dispatched when needed. However, economic conditions in the U.S. are changing. At least two of the scenarios ("Digging in our Heels" and "Double Whammy") create conditions that are likely to favor storage technologies, due to the high cost of fuel for peaking power plants. And the prospects for further lowering the capital costs of storage plants are bright. Clearly, R&D focused on lowering the cost of energy storage plants is a top priority that cuts across all four scenarios.

Transmission and Distribution (T&D) Benefits

Many of the new potential applications for energy storage are related to transmission substations and distribution feeders, and some storage technologies are also uniquely positioned for end-use applications as a demand-response tool. The Federal Energy Regulatory Commission (FERC) has defined a variety of “ancillary services” needed to support the delivery of power to consumers while maintaining overall grid system reliability – and for which the energy storage provider can seek compensation through restructured electricity markets.

Energy storage is particularly well-suited to provide at least two of these ancillary services: system regulation and spinning reserve. Regulation services involve supplying electrical energy in real time to compensate for rapid changes in system load (e.g., mitigating the fluctuating power from wind farms); spinning reserves restore the balance of supply and demand on a system after the sudden loss of a generator or power line, or a sudden, unexpected increase in load. In addition to these power delivery benefits, energy storage can provide other ancillary services (e.g., dynamic reactive energy to the electric transmission system when needed).

The major advantage of energy storage devices for these applications, compared to power generation sources is that energy storage plants do not burn fossil fuel (except for the low fuel burning “hybrid” storage plant called compressed air energy storage). This presents major advantages in either of the two scenarios in which environmental issues are paramount. The avoided emission of carbon dioxide (CO_2) that storage technologies afford makes them essential components in both the “Double Whammy” and “Biting the Bullet” scenarios.

In ancillary service applications, the flexibility of storage technologies produces multiple benefits from a single device (potentially better monetized by electric distribution companies). For example, electric energy storage plants provide both regulation services and spinning reserves at the same time. In addition, storage technologies are preferred in applications where air emissions, noise, and fuel costs are important, or where there is a premium on modularity and prompt start-up. A major conclusion of research reported in a recently-completed joint EPRI-U.S. Department of Energy (DOE) Handbook on Energy Storage for T&D Applications is that, “While storage is not yet the universal solution for the ills of the electric delivery system, as more experience is gained and as technologies improve, storage may one day be ubiquitous in our power systems.”[9]

Large-Scale Storage: Pumped Hydro and Compressed Air Energy Storage

By far the largest application of energy storage in today’s electric power systems is the use of pumped-hydroelectric facilities to provide daily load shifting. The United States currently has 150 such facilities in 19 states providing a total 22 gigawatts of generation capacity. Typically, these facilities consist of two reservoirs at significantly different elevations, connected by large hydro penstocks with a power-generating station between them. Electricity from a conventional power plant is used to pump water from the lower reservoir to the higher one during off-peak

[9] *EPRI-DOE Handbook of Electricity Storage for Transmission and Distribution Applications*. Final report, December 2003. EPRI report number 1001834.

hours. When needed, appropriate gate valves are opened and gravity pulls the water back to the lower level through a hydroelectric turbine to help meet on-peak system loads. Such facilities range in size from hundreds of megawatts to over 2 GW and are capable of discharging at full power for a large number of hours (e.g., 8-12 hours).

However, scarcity of suitable surface topology in the U.S. is likely to inhibit further significant development of electric utility pumped-hydro storage plants. The only other viable large-scale storage technology is compressed air energy storage (CAES). This technology uses electrically to drive compressors to charge an underground reservoir during off-peak hours. Then when needed, air is discharged from the reservoir into a fuel-fired expansion turbine connected to an electric generator. By using electricity for the compression cycle, the fuel normally used by a simple cycle combustion turbine plant is reduced by about 60 percent in a CAES plant.

Only two commercial CAES plants are currently in operation, using underground salt formations to store the compressed air. Demonstrations are needed to prove the commercial viability of CAES in porous rock/aquifers and in hard rock underground formations. R&D is also needed to advance the promising concept of above-ground pipelines to store compressed air for CAES applications. Such pipes, similar in size and pressure to those used to transport natural gas, could be sited within an existing transmission or distribution right-of-way. A further potential CAES advancement is called “adiabatic CAES” – a plant configuration in which no fuel is burned during the generation cycle.

The cost of CAES is a factor of 2-10 times lower than any other bulk storage technology. Hence, CAES represents the single best hope for a larger fleet of economical, large-scale storage facilities – a capability that is sorely needed in any scenario with sustained high natural gas prices. Table 4-1 shows today’s approximate costs of various energy storage technologies.

Table 4-1
Approximate Costs of Storage Technologies

Technology	$/kW	$/kWh*	Hours	Total Capital Cost ($/kW)
Compressed Air				
- Large (100-300 MW)	350	1	10	360
- Small (10-20 MW)	370	30	3(5)	460(520)
Pumped Hydro				
- Conventional (1000 MW)	1100	15	10	1250
Battery (target) 10 MW				
- Lead Acid	120	150	2	420
- Advanced (Flow)	520	50	2(5)	620(770)
Flywheel (target) 100 MW	150	300	2	750
SMES (target) 1000 MW	120	300	2	720
Supercapacitors				
- Best today	120	12000	1/60	320
- Target	120	120	1/60	122

*This capital cost is for the storage reservoir, expressed in $/kW for each hour of storage. For battery plants, costs do not include expected cell replacement.

Battery Energy Storage

Battery plants store energy by relying on the electrochemical changes of sets of chemicals during charge and discharge. For example, in a lead-acid battery, lead is converted to lead oxide during charge and back to lead during discharge. The electrolyte (sulfuric acid) is the medium in which the charging and discharging ions move from the electrodes (positive or negative) during the charge and discharge process. The lead-acid battery is a mature and commercial energy storage technology. Battery plants in southern California and Puerto Rico demonstrated the technical and economic feasibility of lead-acid battery plants for load shifting, regulation duty, frequency support, and grid VAR support. Both of these plants, and others were technically successful. The areas of concern for lead acid battery plants are their high capital cost when more than one or two hours of discharge is needed, high maintenance costs, and cyclic life when used in a deep discharge application. However, for spinning reserve duty, they are one of the least expensive and high performance options available today.

Advanced battery plants (i.e., those not using the lead-acid battery electrochemistry) use the electrochemical properties of, for example, sodium sulfur, zinc-bromide, or vanadium at two different valence levels. Advanced battery options take advantage of the attributes of lead-acid plants – the overall plant is built using an integrated set of battery modules sited close to the end user. However, advanced battery plants have a higher energy density than lead-acid plants, and they offer the promise of lower capital and maintenance costs, modularity, and siting potentially in close proximity to consumers. These advantages, along with the fast time response capability of any battery plant, make advanced battery plants attractive for the "Double Whammy" and "Digging in our Heels" scenarios.

The sodium-sulfur battery, which is offered commercially under the trade name NAS, is based on a high-temperature reaction between sodium and sulfur, separated by a ceramic electrolyte – a configuration that has very high energy density, excellent stability, robust cycling, and minimal onsite maintenance requirements. Tokyo Electric Power Company (TEPCO) has already installed numerous NAS units in the 1-6 MW range to provide load leveling and uninterruptible power at the substation level. In 2002, American Electric Power (AEP) hosted the first NAS battery demonstration in the U.S., with the cooperation of EPRI and other partners. Although initial cost remains an issue, further demonstrations are planned at AEP and the New York Power Authority, with each focusing on different duty cycles, ownership business conditions, and expected application benefits. With these demonstrations and other commercial applications, NAS manufacturing capacity is expanding, which will lead to lower prices, making this technology increasingly attractive for transmission and/or distribution applications.

Other emerging advanced batteries are now being developed for use in hybrid and plug-in hybrid electric vehicles (PHEVs). These battery technologies will likely have excellent potential for stationary applications as well – either on the grid or at consumer locations. Here, both nickel-metal hydride (NiMH) and lithium ion (Li-ion) batteries have demonstrated energy storage capabilities that are much higher than conventional lead-acid batteries (of equal weight) and can function effectively over 5-10 times as many deep discharge cycles. Given a sufficient R&D and manufacturing effort that successfully demonstrates PHEVs, the costs of NiMH and Li-ion batteries could be reduced by as much as 80 percent in a relatively short timeframe, making them more affordable for stationary uses.

One particularly intriguing possibility is the use of a PHEV as a backup power unit in the home. The vehicle would normally be charged through a simple electrical hookup in the garage. Designers say that the charging unit could be configured to automatically feed electricity from the vehicle batteries back into the house wiring to cover basic electricity needs during, for example, a local power outage.

For long-duration discharge applications, a more fundamental departure from traditional battery design is being considered – so-called flow batteries. Generically, these batteries utilize chemically active materials contained in the fluid electrolyte rather than in solid electrodes. The advantage of this design is that the battery energy rating depends on the volume of the electrolyte, while the power rating depends on the size of the reaction cell stacks. As a result, the cost to extend the discharge time of a flow battery system only depends on the size of the tanks used to hold the electrolyte, which is low compared to the cost of changing the number of cells in a non-flow type battery system. Thus, flow battery systems are especially attractive for applications that require energy discharge for several hours. The corresponding disadvantage is that flow batteries tend to be complex systems with pumps, plumbing, and other auxiliary components. Two types of flow batteries are now available commercially – the vanadium redox battery (VRB) and the zinc-bromine battery.

Regardless of the type of advanced battery, R&D is needed to reduce their cost, improve their lifecycle performance, and develop fully integrated, cost-effective systems for utility application. But underlying this discussion of batteries is a larger issue: batteries may not be the clear winner in the competition for the best small-scale, modular storage technology. Depending on the application, also vying for this title are flywheels, supercapacitors, and superconducting magnetic energy storage (SMES) systems. To ensure that the most beneficial small-scale storage option ultimately comes to fruition, especially to prosper in challenging scenarios like “Double Whammy,” all of these technologies need to be further developed and compared for alternative duty cycles and applications.

Flywheels and Supercapacitor Electric Energy Storage

Two modern versions of technologies that have evolved substantially from 19^{th} century origins are competing to provide voltage support and short-term electric power ride-through capability – flywheels and supercapacitors. The major advantage of flywheels over batteries is that they are capable of several hundred thousand full charge-discharge cycles and thus have much better cycle life performance. This makes flywheels attractive for frequency regulation duty. In addition, their power output and stored energy capacity can be sized independently. During charge-up, a flywheel is accelerated by an electric motor, which later acts as a generator during discharge.

Low-speed flywheels are usually designed for high power output, while high-speed units can be designed to provide either high power or high energy discharge capability. The most common power quality application is to provide ride-through of power interruptions up to about 15 seconds, or to bridge the transfer from one power source to another during power interruptions or voltage sags. Multi-megawatt flywheel systems have been installed at power quality-sensitive consumer sites such as communications facilities and computer server centers; and commercial systems can be used for reactive power support, spinning reserve, and voltage regulation as well.

Advanced electrochemical capacitors, also known as supercapacitors or ultracapacitors, are distinguished by storing energy using an electrolyte solution between two solid conductors, rather than by the more common practice of separating the electrodes with a solid dielectric. This arrangement gives the devices much greater capacitance and energy density than conventional capacitors, and also enables them to be made very compact (about one $10{,}000^{th}$ the size of regular capacitors per unit of stored energy). Like flywheels, supercapacitors have been used in power quality applications, such as for ride-through and power transfer/bridging applications, as well as for energy recovery in mass transit systems during the braking operation at each transit station. Supercapacitors also have the capability to have very high cycle life, in the range of hundreds of millions of cycles, which makes them very attractive for the frequency regulation, FACTS-storage, and/or regulation duty applications.

Superconducting Magnetic Energy Storage

For fast discharge of a large amount of energy, a superconducting magnetic energy storage (SMES) system is very attractive. This technology directly exploits recent advances in high-temperature superconducting materials and cost reductions in AC-DC-AC (alternating current to direct current to alternating current) power electronic inverters. Energy is stored in the magnetic fields produced by continuously circulating current in a DC superconducting coil. Because SMES devices suffer from none of the thermodynamic losses inherent in the conversion of stored chemical energy (i.e., in batteries) or mechanical energy (i.e., in flywheels), SMES devices have very high round-trip charge-discharge efficiency (about 95 percent).

There are several commercial “micro-SMES” applications at the 1-3 MW level, capable of discharging more than a kilowatt-hour of energy in about one second. Such micro-SMES units typically provide protection against voltage sags for sensitive industrial equipment. In addition, a commercial product is designed to provide reactive power for voltage support on distribution lines, with real power injection also available to help consumers ride through grid system disturbances. Although extensive design and development programs have been conducted to create large-scale (10-100 MW) SMES units, R&D to substantially reduce cost will be required before bulk storage SMES applications are economically feasible.

The first SMES device to be deployed at the transmission system level is now being prepared for service at the Tennessee Valley Authority. Called the SuperVAR dynamic synchronous condenser, this device will help stabilize grid voltage, increase grid reliability, and help maximize transmission capacity. Dynamic synchronous condensers serve as “shock absorbers” for the grid by dynamically injecting or absorbing reactive power (measured in volt-amperes reactive, or VARs) to minimize sudden and large voltage fluctuations. The cycle life of SMES devices should be very high -- in the range of hundreds of millions of cycles -- which is similar to supercapacitors.

Additional Benefits of Energy Storage Plants

Storage plants increase the viability of complementary technologies. In the "Double Whammy" scenario, for example, renewables must play a key role. Storage technologies raise the value of renewables by smoothing out the minute-to-minute or hour-to-hour fluctuations in the output of wind turbine and photovoltaic facilities. Storage can also act as a hedge against the possibility that these technologies may provide little or no output on any given day, given weather variations. While this benefit is particularly clear in the high gas price, high environmental awareness scenario, it can also make enough of a difference to transform renewables from a difficult-to-justify technology to a viable one in scenarios such as "Digging in our Heels" and "Biting the Bullet." Figure 4-1 summarizes the opportunities for energy storage plants in the various scenarios. Figure 4-2 lists R&D needs for each of the major energy storage options.

"In the broadest sense, storage devices may be the most important element of power systems in the future," the EPRI/DOE storage handbook concludes. "Storage devices, if inexpensive enough and reasonably efficient, would be of highest value if placed at or near consumers with variable loads. The second-best location is on utility [distribution] feeders, followed by [applications at] substations and the transmission system. If these devices are operated for the common good, the high voltage [transmission] wires could be nearly base-loaded and the reliability of the system as a whole would be much improved."[10]

Conclusions

The interaction of technological advances and the actions of numerous industry entities (e.g., regulators, economists, manufacturers, utility companies, and customers) shape the path that generation companies, system operators and planners take. The eventual technical or economic outcome cannot yet be predicted with confidence. Thus, R&D in the energy storage area should initially cover many types of potentially attractive technology options. The specific storage options that require additional funding for component improvements and field demonstrations will be winnowed down based on the results of the earlier efforts.

Regardless of how the industry's business structure evolves, the need for an instantaneous, reliable and low-cost supply of power will remain. Utilities will develop strategies to remain competitive in an uncertain future. Energy storage plants are a key element in virtually all of the "what-if" scenarios discussed earlier in this report, because these plants meet present and future requirements of virtually all potential outcomes of the changing electric utility infrastructure.

[10] EPRI-DOE Handbook of Electricity Storage for Transmission and Distribution Applications. Final report, Dec. 2003. 1001834 EPRI.

Key R&D Topics

Critical R&D efforts to advance electric energy storage technologies are presented below:

- Develop and demonstrate flexible AC transmission systems (FACTS) with energy storage
- Develop electric energy storage value proposition for the re-regulated utility industry
- Develop and demonstrate low cost battery and compressed air energy storage systems
- Develop energy storage integration and evaluation analyses for distributed resources, renewables and the IntelliGrid
- Develop and demonstrate superconducting-storage substation
- Develop and demonstrate renewable generation options with energy storage
- Document the successful operation and economic benefits of existing pumped hydro, battery, and compressed air energy storage plants

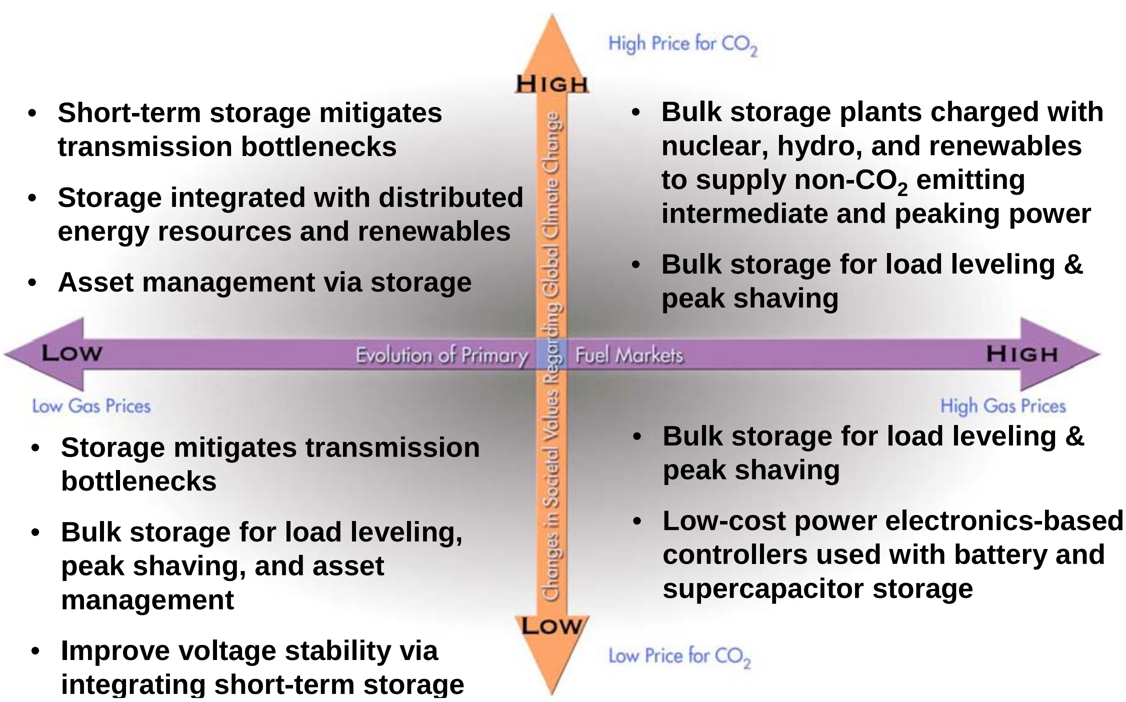

Figure 4-1
Critical Technology R&D Needs in the Energy Storage Area Vary Across the Scenarios.

For the upper right quadrant scenario, bulk storage R&D to address CO_2 emissions is critical. For the upper left and lower left quadrant scenarios, short-term storage R&D to address transmission bottlenecks is critical.

Scenario	"Biting the Bullet"	"Double Whammy"	"Supply to the Rescue"	"Digging in Our Heels"
	High CO_2 prices; Low gas prices	High CO_2 prices; High gas prices	Low gas prices; Low CO_2 prices	High gas prices; Low CO_2 prices
Overview and drivers of technology R&D	Energy storage reduces emissions and competes favorably with other generation options for peak shaving and ramping	Efficient storage plants and those integrated with renewable plants address high natural gas costs and high CO_2 costs	Storage plants are used to peak shave transmission and distribution loads and for spinning reserve to address rapid load growth	Efficient storage plants are used for peak shaving and load ramping to address high premium fuel costs
Technology R&D Gaps: For each scenario, these represent the critical technology R&D needs in the area of electric energy storage.	Develop and demonstrate low-cost battery and CAES plants			
	Develop energy storage integration analyses for distributed energy resources, renewables, and IntelliGrid			
Legend: Very critical (solid red arrow); Critical (dashed orange arrow); Important (dashed blue arrow). Arrows indicate that the R&D need applies to *more than one scenario*	Develop and demonstrate superconducting storage substation			
	Develop and demonstrate renewables with storage			
	Develop energy storage value proposition for the re-regulated utility industry			
	Develop and demonstrate power electronics-based controllers with energy storage			

Figure 4-2
EPRI Scenario and Technology Development Matrix for Electric Energy Storage

5
TECHNOLOGY R&D NEEDS: THE ENVIRONMENT

This section covers technology R&D needs in the environmental area. It addresses the following topics:

- Carbon capture, transport, and sequestration
- Emissions reduction and control
- Environmental science and technology, including climate change policy, water availability and quality, air pollutants, magnetic fields, and lifecycle and total ecosystem approaches.

Carbon Capture, Transport, and Sequestration

Overview

Fossil fuels – primarily coal, oil, and natural gas – account for nearly 80 percent of the world's primary energy consumption. While driving the engine of global economic growth and prosperity, fossil fuel combustion also creates carbon dioxide (CO_2), the predominant greenhouse gas. By the dawn of the 21^{st} century, CO_2 emissions associated with human activity had grown to more than $6x10^9$ metric tons, or 6 giga-tonnes, of carbon per year, and the concentration of CO_2 in the atmosphere had risen from 280 parts per million by volume (ppmv) in pre-industrial times to about 370 ppmv.

Continued growth in energy demand – especially in developing countries – is projected to further increase global emissions of CO_2 and its atmospheric concentration. This trend conflicts with the scientific consensus that stabilizing the atmospheric concentration of CO_2 and other greenhouse gases is necessary to avoid adverse effects on the world's climate.

Many options exist – at least in theory – for reducing the net flux (i.e., additions minus removals) to the atmosphere of CO_2 from electricity production, transmission, distribution, and use. These include the following:

- Substitution of non-fossil generation (e.g., renewable energy, nuclear energy) for fossil-fueled generation (see "CO_2-free" portion of Figure 5-1)
- Fuel switching (e.g., from coal to natural gas, which has a lower CO_2 emission rate), and development and deployment of advanced, high-efficiency coal generation technologies (see "high-efficiency CO_2-emitting" in Figure 5-1)
- Development of cost-effective direct CO_2 capture (e.g., in IGCC plants equipped for CO_2 capture), transport, and sequestration options (see "CO_2-capture capable" in Figure 5-1)

- A broad range of "non-generating options" (see Figure 5-1):
  - Conservation of energy
  - Improvement of efficiency in electricity transmission, distribution, and use[11]
  - Substitution of more-efficient end-use electric technologies for less-efficient alternatives
  - Sequestration (i.e., long-term storage) of atmospheric CO_2 by changes in land use and forestry practices
  - Sequestration of atmospheric CO_2 by chemical reactions and removal in the ocean
  - Use of electric-drive systems to increase transportation efficiency and thereby reduce net CO_2 emissions (e.g., hybrid vehicles, electric vehicles)

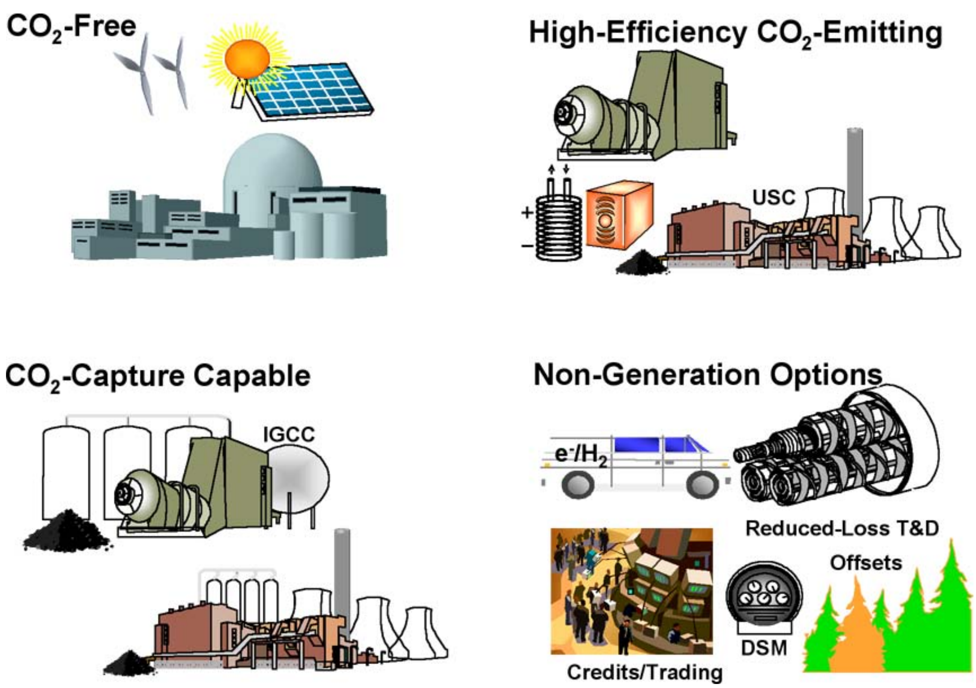

Figure 5-1
Utility Options for Carbon Capture and Sequestration

[11] Using less energy to accomplish society's tasks provides proportional reductions in CO_2 and other emissions. Substantial improvements in energy efficiency may be achieved through industrial process innovation, new materials and manufacturing methods, "smart" products, energy storage, advanced power quality, and real-time communication of energy prices and other vital information.

Unfortunately, none of these options is a panacea. Some are of limited capability or have prohibitively high cost; others may require further RD&D to advance from theory to commercialization; and some may not enjoy public support. Overcoming these and other barriers will require sustained investment in a portfolio of energy technology RD&D that creates a stream of increasingly cost-effective technologies over time. This section addresses RD&D that creates cost-effective CO_2 capture, transport, and sequestration technologies within the electricity industry. Such technologies would provide significant benefits:

- In the foreseeable future (the next few decades), if CO_2 capture and sequestration costs can be reduced, these could provide a means for reducing emissions from the installed base of fossil-fueled generating plants, thus avoiding the high costs of premature retirement of existing capital stock.
- In the longer term, carbon capture and sequestration would provide a means of continuing to use conventional electricity generation technologies in locations where coal is an abundant indigenous resource; this provides benefits including affordable electricity, energy security, and fuel diversity while developing technologies for the ultimate transition to low- or zero-CO_2-emitting power systems. In addition, CO_2 capture technologies may be an important element of advanced generation technologies.
- Although the principal focus of this section is on CO_2 capture and sequestration technologies for the electricity sector, carbon capture and sequestration also could play a critical role in determining the future structure of many other sectors of the economy. For example, the availability of cost-effective CO_2 capture technology for central electricity generating stations would create a route by which emissions from combustion engine-powered vehicles could be reduced by switching to expanded use of electric-drive vehicles, powered by zero/low emitting coal-fired power plants.

CO_2 Capture – Today's Technology and Its Drawbacks

CO_2 separation is a commercial practice in the beverage, chemical, and oil and gas industries. The application of those technologies, however, to remove CO_2 from a coal power plant gas stream, either pre- or post-combustion, is energy-intensive and expensive.

The commercial technology most cited as potentially applicable to capturing CO_2 from the large volumes of flue gas from power plants burning natural gas, oil, or pulverized coal – monoethanol amine (MEA) absorption/stripping – requires pre-cleaning of trace contaminants (e.g., SO_2) prior to scrubbing the CO_2 from the gas with MEA. After gas contact, the scrubbing liquor must be heated to drive off concentrated CO_2 for subsequent sequestration and restore the MEA. The total power consumption for this process (without transport and disposal of the captured CO_2), as a percentage of the output of a plant without it, is nearly 30 percent for a new supercritical unit, according to a major EPRI/U.S. Department of Energy (DOE) study.[12] The "energy penalty" for subcritical plants, which are much more common, is considerably higher. The MEA process is

[12] *Evaluation of Innovative Fossil Fuel Power Plants with CO_2 Removal*, EPRI report number 1000316, December 2000.

estimated to increase the wholesale cost of electricity (COE) for a new supercritical plant by about 60 percent. The cost adder for a retrofit to an existing subcritical plant would, as with the energy penalty, be significantly more. For a new natural-gas-fired, combined-cycle plant, which contains a lower concentration of CO_2 in the flue gas stream, the energy penalty is estimated to be 20 percent and the COE increase to be nearly 70 percent.

New 5-MW pilot work is planned in 2007-08 at an existing PC site to test a chilled ammonia absorption/stripping process, which promises lower energy use and cost based on laboratory-scale tests.

Many other processes based on physical, chemical, and biological principles (e.g., membrane separation, biomimesis, chemical looping, mineralization, microbe/genetic engineering, and oxyfuel combustion) have been suggested for CO_2 capture; all of these are in the conceptual or laboratory phase of development. Oxyfuel combustion is of particular interest because of its simplicity in principle; coal is burned in oxygen rather than air, producing a pure stream of CO_2, which is easily separated from the water vapor also produced. Oxyfuel does pose some challenges, such as the high temperatures produced and the consequent requirement for materials that can withstand these temperatures.

Substantial RD&D is required to bring these options to commercial availability, and some of these technologies may never reach that stage. Today's capture technology may only be economically viable in niche applications, such as where valuable byproducts could be co-produced and sold in the process of disposing of CO_2 (e.g., enhanced oil or gas recovery or coal-bed methane production) or within political boundaries that require CO_2 reductions or impose high fees on CO_2 emissions.

Although still based on solvents, CO_2 capture methods for existing integrated gasification combined-cycle (IGCC) power plants exact a smaller loss in energy output, and this may make IGCC the preferred coal-power technology if CO_2 capture is required. Projections show that removing CO_2 from a synthetic fuel gas produced by coal gasification will reduce the energy penalty and cost of removal significantly, because the volume of gas to be treated is approximately 1/200 that for conventional plants, and the concentration and partial pressure of CO_2 are much higher than in conventional flue gas. The EPRI/DOE study projected an energy penalty of about 5 percent and a power cost increase of 25 percent (relative to the cost of electricity from a new IGCC unit without CO_2 control). Even though the "adder" for CO_2 capture is lower than that for conventional plants, it is still expensive. Thus, even for IGCC plants, significant improvements in CO_2 capture technology will be needed.

Hence, R&D needs in this area include the following (see Section 3 on IGCC and advanced coal combustion for more information):

- Reduce cost of monoethanol amine (MEA) and advanced amine absorption/stripping
- Develop other processes for CO_2 capture in fossil units

In addition to capturing carbon at power generation sites, additional opportunities for CO_2 capture must be explored. To assure that a number of economically viable technologies for carbon capture are developed, a large number of potential concepts must be identified and developed. This involves a search for breakthrough technologies that have the potential to reduce the cost and energy penalties of CO_2 capture by at least 50 percent. Concepts recently discussed include structured liquids (fluids that change from an amorphous to a structured state with the application of an electrical potential, which can capture and release CO_2); biomimesis (the synthetic manufacture of enzymes naturally occurring in nature that can be used to catalyze reactions producing calcium carbonate and other carbonaceous compounds); and clathrates (dry ice/water slush type solids that are stable under the pressures at the ocean floor).

Transporting Compressed or Liquefied CO_2 – Commercially Understood at Small to Moderate Scale

Once CO_2 is captured and compressed or liquefied, numerous uncertainties remain. For example, although transport of CO_2 via high-pressure pipelines (as a supercritical fluid) has been done commercially, it has not been used on the wide scale that would be needed for meaningful CO_2 emissions reductions. Public acceptance of the risk of accidental releases, and the need for extensive new pipelines, will be important issues in siting. There are also technical and safety questions regarding trace contaminants in the CO_2 stream, which affect, for example, materials selection and leak monitoring technology. Even for mixed (i.e., non-purified) gases, however, there is some commercial experience to serve as a point of reference for risk assessments. For about two years, a pipeline has carried CO_2 containing hydrogen sulfide (H_2S) from a coal gasification site in North Dakota to an enhanced oil recovery site in Canada.

Hence, the critical R&D need in this area is to demonstrate larger-scale transport of compressed or liquefied CO_2.

Carbon Storage – A Conceptual Foundation, But With Many Unknowns and Scant Field Work

Although the technical questions are many in the area of carbon storage (see Figure 5-2), the fundamental issue is whether the CO_2 will remain in its disposal location. The information to answer this question needs to be collected so that appropriate models of disposal locations can be formulated and used to predict which locations will assuredly contain CO_2.

Public acceptance of carbon sequestration will vary depending on the locations of disposal sites and the types of disposal technology used. The capacity, effectiveness, and health and environmental impacts of various types of CO_2 disposal and the impact of any inadvertent releases are key areas of scientific inquiry. The potential for long-term trace leakage rates from disposal sites are of interest as well as the risk of rapid releases. If early decisions are made to store large volumes in locations that later turn out to have higher-than-projected leakage, "legacy" problems could result. Key technology R&D needs in the area of assessing the potential health and ecological risks of carbon sequestration include the following:

- Identify the potential health consequences associated with environmental exposures to CO_2.
- Identify the ecosystem risks associated with disposal and release of CO_2.
- For geological disposal, identify plausible exposure scenarios, taking into account reservoir type, chemical or physical changes that might occur subsequent to deposition in the reservoir, and geologic events such as earthquakes that might create unanticipated escape routes.
- Identify the potential health and ecosystem consequences associated with exposure to chemicals resulting from chemical and/or physical changes that might occur over time in geological disposal reservoirs.

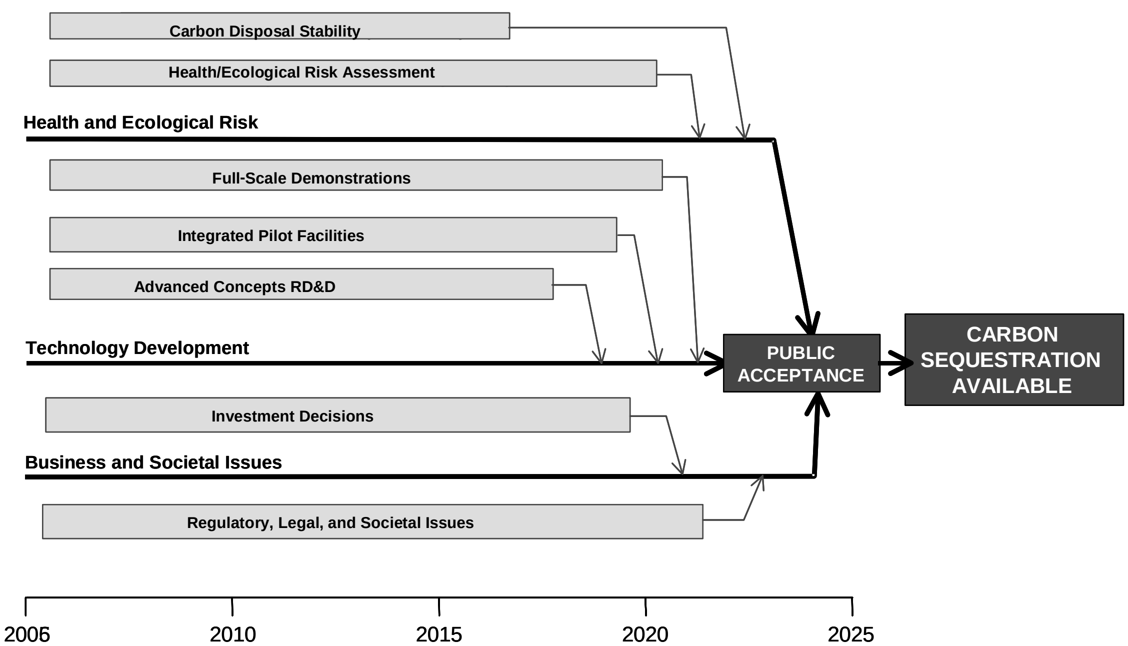

Figure 5-2
Carbon Sequestration RD&D Logic

Geological disposal of massive amounts of CO_2 presents a public acceptance challenge as well as raises technical and legal issues. CO_2 injection is practiced at numerous sites worldwide for enhanced oil recovery (EOR) and enhanced coal bed methane (ECBM), and there is at least one major demonstration in the North Sea where CO_2 is injected in a saline reservoir for disposal. In the current applications of CO_2 for EOR and ECBM, processes have not been optimized for underground CO_2 disposal. Political and siting issues will have to be addressed.

There are several advantages of sequestering CO_2 in deep saline formations – beds of porous sandstones with salty water, alternating with impermeable shales. The capacity of these reservoirs in the U.S. is large – estimated to be able to hold 500 billion tonnes of CO_2. (By comparison, current worldwide CO_2 emission levels are about 6 billion tonnes of carbon per year.) Another advantage is that many U.S. power plants are relatively close to these formations. Although there is evidence that CO_2 may be safely stored in saline aquifers, very little actual CO_2 has been placed into storage. Statoil of Norway has accomplished the only commercial, long-term sequestration of CO_2 in a saline aquifer; the company sequesters the equivalent of what would be produced by a 150-MW coal-fired power plant. R&D needs in this area include a better understanding and characterization of CO_2 in these formations, determination that the CO_2 will not escape from the aquifer (via monitoring) and adversely impact human health or the environment.[13]

Mineralization (reacting CO_2 to form a stable mineral compound) is one mechanism that nature provides to tie up CO_2 in geologic structures for long periods. Unfortunately, reaction times are long, ranging up to millions of years. Several novel processes promise to speed reaction rates and transform captured CO_2 into a truly stable and benign mineral material; however, none are past the embryonic stage of development. In experiments, these mineralization processes have consumed large quantities of energy and generated large volumes of solids per unit of CO_2 reacted. Because minerals such as limestone are widely recognized as a stable form of carbon disposal, mineralization may be the most easily accepted by the public.

The largest carbon sinks are the planet's oceans, but direct ocean disposal (i.e., placing liquid or solid CO_2 deep in the ocean) has already raised public concern about environmental impacts and long-term effects. In the United States, ocean disposal appears to be far less acceptable than expanding the use of CO_2 injection to recover oil, which is already practiced at dozens of fields in the United States, the North Sea, and elsewhere.

Indirect sequestration – removing CO_2 from the atmosphere rather than from power plants – coupled with enhanced terrestrial storage (i.e., by growing more trees and preventing non-essential tree cutting) may offer the advantage of quicker public acceptance, allowing it to be implemented sooner if needed. Relatively low-cost tree planting and wetlands creation programs could serve the special role of "low-hanging fruit" – straightforward steps that can be undertaken first. Ecosystems are limited, however, in the amount of additional carbon they can store, and usually require active management afterward to assure that CO_2 is not inadvertently released (e.g., as can occur during soil tilling for crop planting). Forestation and wetland creation offer other significant environmental benefits in addition to carbon sequestration, such as habitat creation, erosion control, and water purification. Some indirect sequestration options do not lend themselves to quick acceptance or implementation. Ocean fertilization, for example, raises numerous international legal issues and could require decades-long development of complex environmental models.

To enable confident decisions on application of carbon sequestration technologies, utilities and other stakeholders need straightforward, reliable, and accurate tools to make investment decisions. These tools must incorporate comparative economics and be able to account for risk and health and/or environmental impacts. The form and design of these tools will need to be developed and refined through an iterative process with users.

[13] U.S. Department of Energy, Carbon Sequestration Research and Development fact sheet, http://www.fossil.energy.gov/programs/sequestration/cslf/sequestrationfactsheet_06_18.pdf

Hence, the critical R&D needs in this area include:

- Determine the capacity, effectiveness, safety, and health and environmental impacts of various types of CO_2 storage options
- Determine the ability to monitor the underground location and movement of the injected CO_2
- Determine the impact of inadvertent releases from storage locations and methods to mitigate these releases
- Determine whether leakage occurs from storage sites and if so, determine long-term leakage rates and methods to prevent such leakage, including well cement plug integrity
- Optimize EOR and ECBM for underground saline reservoir CO_2 storage
- Explore the feasibility of large-scale indirect sequestration methods

Integrated Pilot-Scale Facilities

Pilot plants are needed to conduct RD&D of promising technologies for capturing and containing CO_2 from power plants fueled by coal, natural gas, or oil. Pilot plant test centers could develop, test, and optimize a range of CO_2 scrubbing processes, piping systems for compressed or liquefied CO_2 transport (including materials selection for real-world gas compositions), and techniques for managing and monitoring underground disposal reservoirs or other CO_2 repositories. The projects would collect long-term data, resolve technical issues where possible, and characterize the technical and economic issues associated with CO_2 capture, transport, and disposal. The test centers would also investigate the potential environmental issues surrounding long-term CO_2 disposal.

Full-Scale Demonstrations

As follow-on efforts to the integrated pilot plant work, and to gain acceptability by industrial users and society, full-scale integrated demonstrations are necessary to assure that scaled-up designs work, operation and maintenance needs are known, actual costs meet expectations, and any health or environmental impacts are minimal. This is particularly true for proving the costs of CO_2 capture and the technical feasibility of disposal. It is unlikely that there will be a single winner, and demonstrations will have to cover a range of generation types, fuels, and disposal techniques. Currently, the only CO_2 capture processes ready for integrated demonstrations are 1) the chemical absorption process (MEA solvent) for a current-generation pulverized-coal plant, and 2) the physical absorption process (e.g., Selexol) for a current-generation integrated gasification combined-cycle plant.

Conclusions

CO_2 capture and sequestration capabilities are clearly needed in the two scenarios with high CO_2 prices (the "Double Whammy" and "Biting the Bullet" scenarios). Carbon capture technologies that are more applicable to natural gas-fired generation are critically needed in the "Biting the Bullet" scenario, while carbon capture technologies for advanced coal combustion and IGCC are more critically needed in the "Double Whammy" scenario. In the other two scenarios, carbon capture technologies for power generation plants are needed but less critical, as a hedge against possible migration to a higher CO_2 scenario. In the "Supply to the Rescue" scenario, natural gas-based capture is important, while in the "Digging in our Heels" scenario, IGCC-based capture is important. In the latter scenarios, construction of plants with the ability to economically phase-in carbon capture is advantageous, but not as critical as the high-CO_2 scenarios (see Figure 5-3).

Key R&D Topics

Following is a list of the key R&D topics for the area of carbon capture, transport and sequestration:

- Demonstrate CO_2 capture, transport, and storage in Advanced Coal pilot and full-scale plants
- Reduce cost of monoethanol amine CO_2 capture process (which currently increases coal plant cost by about 30%)
- Explore advanced concepts for carbon capture
- Improve CO_2 capture in Integrated Gasification Combined Cycle and advanced fossil plants
- Determine capacity, effectiveness, health and environmental impacts of CO_2 storage options
- Develop tools that enable economic evaluation of various sequestration options

Scenario	"Biting the Bullet"	"Double Whammy"	"Supply to the Rescue"	"Digging in Our Heels"
	High CO_2 prices **Low gas prices**	**High CO_2 prices** **High gas prices**	**Low gas prices** **Low CO_2 prices**	**High gas prices** **Low CO_2 prices**
Overview and drivers of technology R&D	Expand to meet environmental requirements	Expand to meet environmental requirements	Consider options for delayed/staged capture	Consider options for delayed/staged capture
Technology R&D Gaps: For each scenario, these represent the critical technology R&D needs in the area of carbon capture, transportation, and sequestration.	Develop processes (reduce costs & optimize system for CO_2 capture in fossil units, including monoethanol amine capture			
	Explore advanced concepts for carbon capture (non-generation)			
Legend: Very critical Critical Important Arrows indicate that the R&D need applies to *more than one scenario*	Determine capacity, effectiveness, safety, & health and environmental impacts of CO_2 storage options			
	Demonstrate CO_2 capture, transport, and storage in pilot plants and full-scale facilities			
	Improve CO_2 capture in IGCC and advanced fossil plants			
	Develop tools for economic evaluation of sequestration options			
	Prevent storage leakage and develop mitigation methods			

Figure 5-3
EPRI Scenario and Technology Development Matrix for Carbon Capture, Transportation, and Sequestration

Emissions Reduction and Control

Overview of Emissions Control for Coal-Fired Power Plants

Regulators are requiring new coal plants to reduce criteria pollutant emissions by almost an order of magnitude, relative to the norms for the previous generation of plants. Thus, the key to obtain a permit to construct a highly efficient coal plant in most scenarios is the ability to incorporate superior, state-of-the-art emission controls, independent of provisions for future retrofit of carbon dioxide (CO_2) controls. Many expect that requirements in the not-too-distant future will be a level of emissions control that can be called "near zero emissions" (NZE). Qualitatively, NZE is obtaining emissions levels that are virtually equivalent to emissions from natural gas-fired power plants, with the exception of CO_2.

Current emission controls may be able to reach NZE levels under optimum conditions with certain fuels, such as the low-sulfur Powder River Basin (PRB) coal found in the huge deposits in Wyoming and Montana, and/or with enough pollutant capture technologies in series. However, even here, two challenges remain:

- To achieve these ultra-low levels continuously (e.g., avoiding "blips" due to transients, non-uniformities, and broken bags in baghouses for particulate control)
- To simultaneously maintain the cost of the power plant at current or lower costs

The concern about short periods of uncontrolled emissions stems from the fact that a plant that must meet very low average emission levels (e.g., less than or equal to 20 ppm) over a period of time will fail to do so if it experiences even just a single 24-hour period of uncontrolled releases. For example, a boiler that burns 2.3 percent sulfur coal (equivalent to 2000 ppm in the flue gas), that must meet a 20 ppm annual average sulfur dioxide (SO_2) emission level, and that normally operates at 18 ppm, would exceed the 20 ppm limit by 3.2 ppm if a 24-hour outage of the SO_2 scrubber forced the plant to bypass the scrubber. This example is presented graphically in Figure 5-4 in terms of annual SO_2 emissions.

This section focuses on new coal plants and assumes that existing coal plants would be replaced by new plants to meet NZE levels. Some of the topics presented here might be transferable to existing plants, although the addition of devices such as polishing systems might make existing units noncompetitive in some scenarios with newer, higher-efficiency plants that have high-performing environmental controls built into their design.

In addition to managing the inevitable temporary upsets, an NZE plant must be designed to optimize all functions that affect pollution control performance in order to meet these ultra-low emission levels. These functions include the following:

- Uniform (or purposefully skewed) flow distribution into each control device
- Elimination of leakage

- Minimum flue gas temperatures at the outlet of the air preheater to reduce equipment size (i.e., capital cost), improve thermal cycle efficiency, and reduce the parasitic energy requirements of emissions control equipment

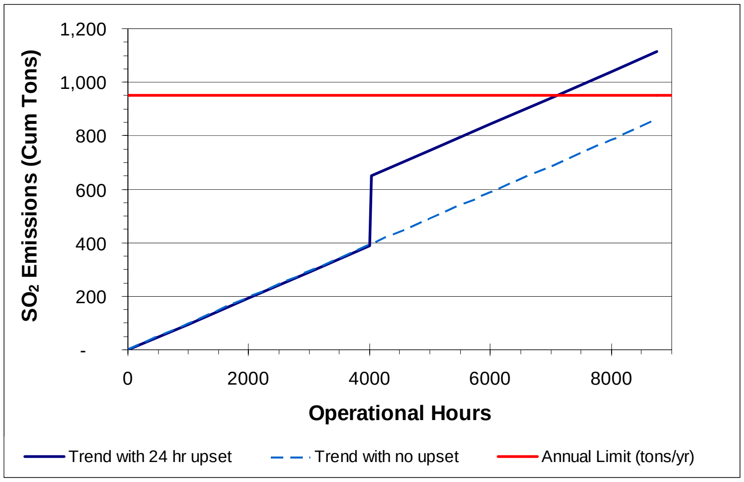

Figure 5-4
Example Annual Impact of Short Period of Uncontrolled Emissions

Near Zero Emission Goals for Coal-Fired Power Plants

Table 5-1 shows current emission limits, as achieved in recent Best Available Control Technologies (BACT) plant permits.[14] The table also presents EPRI's R&D goals to achieve NZE levels in future plants.

Table 5-1
Current Emission Limits and Near Zero Emissions (NZE) Goals
(lb/MBtu unless otherwise noted)

	Nitrogen Oxides (NO_x)	Particulate Matter (PM)	Sulfur Dioxide (SO_2)	Sulfur Trioxide (SO_3)	Mercury (Hg)
Current	0.07	0.011	0.15	—	—
Near Zero Emissions (NZE)	0.01	0.001	0.006	< 1 ppm	< 0.1 µg/Nm^3

[14] *Status and Performance of Best Available Control Technologies*, EPRI report number 1008114, March 2005.

Table 5-2 shows the NZE goals for four pollutants, as specified by the DOE, the Canadian Clean Power Coalition, and the Coal Utilization Research Council (CURC) Roadmap.

Table 5-2
Near Zero Emissions (NZE) Goals

	Lowest Permit Level (lb/MBtu)	Department of Energy*	Canadian Clean Power Coalition**	CURC Roadmap (2020)
Nitrogen Oxides (NO_x)	0.07	< 0.01	~ 0.01†	0.01
Particulate Matter (PM)	0.015 (f/c)	0.002	~ 0.005	< 0.01
Sulfur Dioxide (SO_2)	0.022	> 99%‡	~ 0.01†	0.04 (Bit) SO_3 < 2 ppm
Mercury (Hg)	80–90%	95%	0.7 lb/TBtu	80–95%

* DOE goals are from their Clean Power Program Roadmap for new plants.

** Canadian goals are from their Canadian Clean Power Coalition report for all plants, including retrofits, and are 30-day rolling averages. They are actually output based (g/MWh), but were presented as flue gas concentrations. EPRI converted them further to lb/MBtu using typical correlations.

† ~ 5 ppm @ 3% O_2.   ‡ 99% @ 3% S coal ~ 25 ppm or ~ 0.05 lb/MBtu.

Overview of R&D Needs for Coal-Fired Power Plants

Current air pollution controls on coal-fired power plants are able to reduce emissions of NO_x, SO_2, SO_3, and mercury to very low levels, but usually not to NZE target levels on all coals and consistently throughout the year. Therefore, technology advances, enhanced instrumentation, and, most likely, a final polishing step would be required to attain the NZE target levels. Hence, the air pollution control design for an NZE plant could consist of the following components:

- For eastern bituminous coal: Advanced staging; advanced selective catalytic reduction (SCR) for NO_x control; advanced electrostatic precipitator (ESP) or baghouse for particulate control; a method to enhance mercury oxidation; wet flue gas desulfurization (FGD) for SO_x control with a wet ESP as mist eliminator; and, possibly, a polishing scrubber using highly reactive, clear liquor reagent and the wet ESP located at its outlet
- For Powder River Basin (PRB) coal: Advanced staging; advanced SCR; chemically-treated activated carbon; spray dryer/baghouse (advanced bag material); and possibly a polishing baghouse with sorbent injection for any remaining pollutants

To achieve this, R&D would be needed in emissions control technology to reduce NO_x, SO_x, particulate, and mercury.

Technology R&D Needs for NO_x Control in Coal-Fired Power Plants

Advanced Staging. The NO_x controls that are being installed in new pulverized coal boilers today are low NO_x burners, over-fire air (OFA), and SCR. By diverting enough air from the flame zone to the OFA region, the flame zone can be operated at stoichiometries as low as 0.75 with some fuels, thereby generating quite low amounts of NO_x. However, such "advanced staging" is limited by the concomitant increase in carbon monoxide (CO) and unburned carbon (UBC), as well as fireside waterwall corrosion with many coals.

One possible approach to alleviate increased CO and UBC issues is to use a boosted over-fire air (BOFA) system. BOFA enhances upper furnace mixing between the OFA and the fuel-rich flue gas, thereby minimizing the pockets of poor mixing that can exacerbate these undesirable side effects. The potential benefit of BOFA is the attainment of deeper levels of staging, which translates into lower NO_x emissions than achievable with standard OFA, while maintaining acceptable UBC and CO levels.

A critical drawback with advanced staging is the increased corrosion of waterwall tubes in boilers firing medium or high sulfur coals. Plant operators facing this issue in existing plants consider spray coatings or weld overlay to minimize the waterwall wastage. Further work is needed on 1) advanced materials, such as bimetallic tubes in and directly above the burner belt that can withstand the corrosive environment, and 2) fuel/air management to minimize deposition of corrosive partially burned, iron-containing coal particles on the tube walls.

Improved SCR Flow Distribution. The NO_x reduction capability of an SCR catalyst is determined by the combination of catalyst activity and gas/catalyst contact. Several suppliers are competitively engaged in developing and offering the "best" catalyst, and have a wealth of experience in this area. Further, with some SCR systems achieving up to 93 percent ΔNO_x, the catalyst activity may already be good enough to achieve higher NO_x reductions given sufficient gas/catalyst contact. Currently, SCR system designers make great efforts to present very uniform flue gas flow, temperature, and ammonia (NH_3)/NO_x profiles to the SCR catalyst at the entry. While further improvements are possible here, the greatest gain may come from ensuring that successive catalyst layers are also presented uniform profiles at their respective inlets.

In addition to enhancing NO_x removal efficiency, an added challenge for advanced SCR systems will be to minimize oxidation of SO_2 while simultaneously increasing mercury oxidation to a soluble compound (for subsequent removal in flue gas desulfurization). Although already an issue, this will increase in importance as SO_3 emissions are themselves regulated to near zero levels. In addition, minimization of ammonia levels (e.g., beyond what is currently necessary to avoid formation of ammonium bisulfate for air heater protection), may also need to be addressed.

Success in advanced staging and improved SCR catalyst reactivity and flow distribution may enable PRB-fired units to achieve less than 0.01 lb/MBtu (0.08 lb/MBtu at the economizer exit and 90 percent reduction from this level across the SCR). For bituminous coals, assuming the fireside corrosion issue can be resolved, the achievable level may be 0.02 lb/MBtu (0.2 lb/MBtu at the economizer exit and 90 percent further reduction across the SCR). Greater NO_x reductions may be achievable if a carbon/ash separator is installed to beneficiate the carbon-rich ash. This enables the plant to realize potential allowance sales or avoid another processing step for NO_x, while still maintaining ash sales and avoiding the undesirable practice of ash disposal.

Technology R&D Needs for SO_x Control in Coal-Fired Power Plants

For SO_2, advanced wet scrubbers can achieve greater than 99 percent collection efficiencies, although careful attention must be paid to materials of construction, management of the process chemistry, and gas flow uniformity into and through the absorber vessel. While modern scrubber installations in Europe and Japan routinely emit less than 10 ppm of SO_2, these units clean flue gas from power plants burning less than or equal to 1.0 percent sulfur coal (and shut down one month each year for maintenance). Therefore, supplemental controls may be needed at plants burning a higher sulfur coal to achieve these same very low SO_2 levels.[15] Bubbling bed or fountain absorber systems (Chiyoda CT-121, Alstom's FlowPac, and MHI/Advatech's double contact flow scrubber) may provide enough liquid/gas contact to allow less than 10 ppm of SO_2 escape, even from a high sulfur coal, but this remains to be demonstrated at full-scale and over extended periods of time.

Other potential alternatives to achieving ultra-low NZE goals for SO_2 include additives such as dibasic acid used in a scrubber designed to remove 99 percent SO_2 without the additives, more reactive reagents such as ammonia or sodium, or a polishing step that uses a highly reactive reagent. Ammonia and sodium can be expensive, unless the solid products – typically fertilizer – can be sold at a reasonable price and/or the active reagent can be produced from a lower cost compound of the reactive species (as advertised for the Airborne process). Using these, or other even more reactive reagents such as hydrogen peroxide, may be economically feasible in a polishing step, where the inlet SO_2 would be very low. In such a configuration, the reagent consumption, which is proportional to SO_2 removed, would also be low. In addition, furnace sorbent injection, with a cavity at the optimum temperature window, can remove about 50 percent of the SO_2, thereby presenting the scrubber with a flue gas similar to that from a low-to-moderate sulfur coal.

Technology R&D Needs for Particulate Control in Coal-Fired Power Plants

Current ESPs and baghouses can achieve emission levels as low as 0.005 lb/MBtu when fine tuned and/or operating with new, but conditioned, bags. To ensure consistent particulate emissions at this low level over all coals and throughout the running time between outages will probably require the addition of technologies that provide the margin via incremental improvements. These include the following:

- Advanced power supplies that respond more quickly to ash property changes, handle high resistivity dust better, and greatly reduce rapping re-entrainment
- An agglomerator upstream of the ESP or baghouse to reduce the fine particle loading
- A polishing device inside the ESP, such as the novel sieving ESP or last field wet ESP

[15] Amine-based CO_2 capture systems require incoming SO_2 levels to be less than 5-10 ppm, depending on the developer's estimate.

For baghouses, the challenge is to develop and demonstrate bag materials that are more durable and minimize the appearance of pinholes, tears, and other material damage sites.

Technology R&D Needs for Mercury Control in Coal-Fired Power Plants

Achievable mercury emission levels or percent reductions are highly coal specific. To ensure 95 percent removal, the following enhancements would be needed (see Figure 5-5):

- Coal cleaning or upgrading to remove the first 35-70 percent of the mercury. If coal processing removes 50 percent of the mercury, the plant systems need to remove only 90 percent of the remaining mercury to achieve a total 95 percent reduction.
- Power plants firing medium-to-high sulfur eastern bituminous coal, especially those with chlorine content in the coal of less than 400 ppmw, will probably need a method of boosting the percent mercury that is oxidized to a soluble compound (e.g., by the flue gas and SCR) before entering the FGD. Injection of a bromine compound into the boiler may serve this purpose, but this approach has not been tested in this configuration and with a 95 percent removal goal.
- Units firing a lower sulfur coal could use a TOXECON™ system to capture mercury.[16] A correctly designed TOXECON with a high permeability, durable fabric material may provide 95 percent mercury capture. If combined with 50 percent mercury removal via coal cleaning, this level should be achievable, but has not yet been demonstrated.
- Power plants firing PRB may be able to consistently achieve 95 percent mercury removal using a spray dryer/baghouse and chemically-treated activated carbon. Plants equipped with an ESP/FGD will probably need both halogen injection into the boiler and a mercury-specific catalyst in the back-end of the ESP. This combination needs to be tested after the current R&D on halogen addition to the boiler and mercury-specific catalysts is completed.
- The polishing step suggested for NO_x, SO_2, and particulate, above, could also serve as a polishing step for mercury if the clear liquor solution contains chemicals that enable it to absorb mercury.

[16] Currently, a significant amount of fly ash from coal plants is sold to cement makers for use as a concrete additive. This market benefits the environment by reducing CO_2 emissions from cement plants and minimizing landfill. However, conventional sorbents, which are captured along with fly ash, change the properties of the ash and render it unsuitable for use in concrete. TOXECON™ technology avoids this contamination by separating the capture of fly ash from the collection of mercury-containing sorbent. TOXECON works by delaying sorbent injection into flue gas until after the fly ash has been collected in a plant's primary particulate filter; the mercury-laden sorbent is then captured in a secondary filter, or baghouse, installed further downstream.

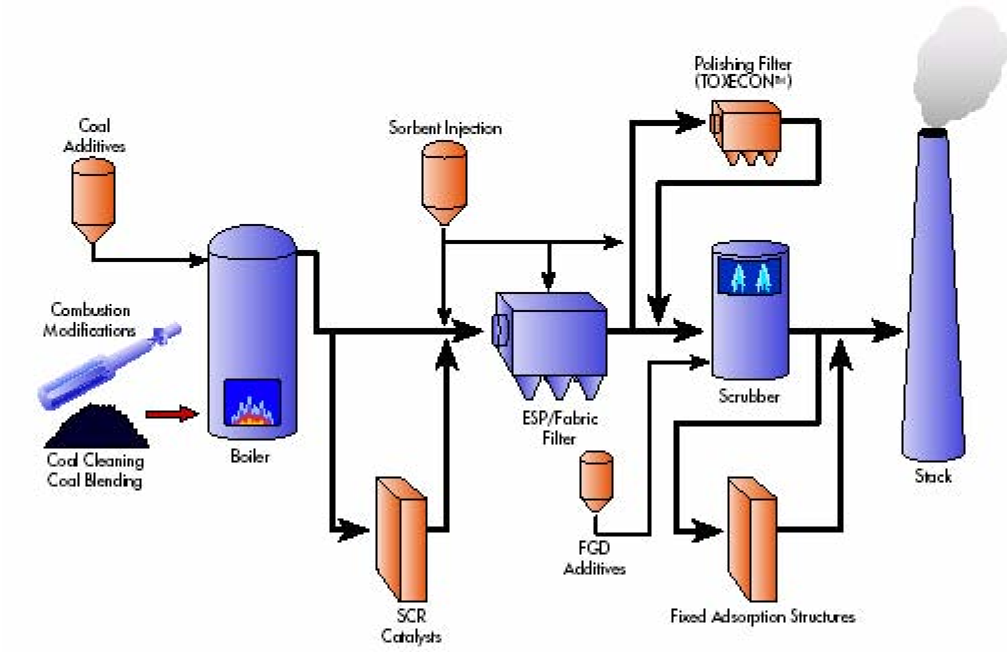

Figure 5-5
A number of approaches are being investigated for controlling mercury emissions from coal-fired power plants.

Potentially beneficial modifications of the fuel or combustion process include coal cleaning, coal blending, and control of the mixing of air and coal during combustion. Options to increase the removal of mercury by scrubbers, which are already on the system to control SO_2 emissions, include adding in SCR (which also reduces NO_x emissions) or catalysts and additives designed specifically to convert the mercury to a scrubbable form. Finally, several mercury-specific approaches are being developed – injection of activated carbon or other sorbent material into the flue gas, sorbent-based polishing filters, and fixed absorption structures. Photo courtesy: *EPRI Journal.*

Additional R&D Needs for Coal-Fired Power Plants

Additional technology R&D needs in the area of power plant emissions from coal-fired power plants include the following:

- Minimize and accurately predict Toxic Release Inventory (TRI) emissions (e.g., arsenic, selenium, lead, chromium, dioxins, hydrochloric acid, and hydrofluoric acid)
- Attain greater than 90 percent utilization of solid combustion products from coal-fired power plants
- Optimize emissions control during plant startups and shutdowns
- Minimize ammonia emissions from plant SCR systems
- Address water resource use limitations; improve water use, cooling designs, and water purification and treatment equipment and processes

- Test and establish valid data of license limiting emissions such as hazardous air pollutants (HAPs), NO_x and other criteria pollutants, as well as solid and liquid discharges, for each newly developed process

Emissions From Combustion Turbine Power Plants

Combustion turbine (CT) power plants (in either simple cycle or combined cycle arrangements) primarily combust natural gas today. Natural gas is a much more clean burning fuel than coal. Because natural gas contains no sulfur or mercury, SO_x and mercury control is not needed. Particulate control is also not needed at natural gas-fired power plants. The primary pollutant that requires emissions control in natural gas-fired power plants is NO_x. Such control is typically accomplished via a combination of pre-combustion control (e.g., via use of dry low NO_x, DLN combustors) and post-combustion control (e.g., via selective catalytic reduction, SCR).

When burning natural gas, DLN lean premixed combustors have consistently achieved very low (single-digit ppm) NO_x levels. These combustors require frequent tuning, as they are susceptible to even small changes in air/fuel splits caused by even seasonal changes in ambient conditions. Also, their operation in lean combustion mode causes a thermal acoustic effect and pressure dynamics that are transmitted to the structural parts of the machine; these instability conditions must be avoided in the machine while maintaining low NO_x levels – a challenge that reduces the turndown (ability to operate at partial load) of these machines. These combustors are also highly sensitive to any changes in fuel quality or fuel type, including liquid fuels or syngas. These complexities are discussed more fully in the section on natural gas-fired generation technologies.

In CTs, SCR is used to further control NO_x emissions, as well as carbon monoxide, CO, emissions that tend to rise as NO_x levels decrease. Contaminants in the air that collect on the catalyst used in SCR systems can lead to accelerated deactivation of the catalyst in medium to high temperature applications typical of simple cycle CT operation. Burning syngas exacerbates this problem due to the presence of even more contaminants. Some concern has been raised about the impact of emissions of volatile organic compounds (VOCs) and formaldehyde from CTs, but regulation is indirectly tied to overall CO emission levels.

Research needs in the area of emission control for CT power plants include the following:

- Further develop technologies for automated online trimming of air/fuel splits to optimize DLN combustor operation
- Develop DLN combustors that can accommodate a wider variety of fuels, including liquid fuels (such as oil or biodiesel) and syngas at low emissions levels
- Address the adverse impact of contaminants in syngas on SCR catalysts
- Identify ways and technologies that enable CTs to operate efficiently and with low emissions at part-load operation
- Characterize and minimize emissions of VOCs and formaldehyde from natural gas-fired power plants

Conclusions

Recent new rules on mercury emissions limitations mean that technology R&D in this area is needed in all scenarios (see Figure 5-6).

In both the “Biting the Bullet” and “Double Whammy” scenarios, increasingly stringent regulatory mandates will require proactive compliance to reduce emissions across a range of pollutants. This mandate will apply to all fossil fuel-fired power generation. While technologies to attain near-zero emissions will be a key part of these scenarios, advances in utilization of combustion products and reduced water use are also needed.

In the “Double Whammy” and “Digging in our Heels” scenarios, new focus on IGCC and advanced coal combustion to address high natural gas prices will require attention to emissions control issues relevant to these power generation technologies. In the “Supply to the Rescue” scenario, regulatory mandates on emissions controls are likely to be less stringent but will still pose significant challenges.

Key R&D Topics

Following is a list of the key R&D topics for the area of emissions reduction and control technology:

- Reduce cost of emissions control for fossil fuel-fired power generation
- Reduce mercury emissions from fossil power generation by about 95%
- Reduce nitrogen oxides and sulfur oxides emissions from fossil power generation to near-zero levels
- Address water use limitations by reducing or eliminating water use
- Attain greater than 90% utilization of combustion products from fossil power generation
- Ensure consistent particulate emissions at low levels over all fuels and load levels
- Document and report on the emission reduction value of electric transportation in on-road and off-road applications

Scenario	"Biting the Bullet"	"Double Whammy"	"Supply to the Rescue"	"Digging in our Heels"
	High CO_2 prices; Low gas prices	High CO_2 prices; High gas prices	Low gas prices; Low CO_2 prices	High gas prices; Low CO_2 prices
Overview and drivers of technology R&D	Proactively comply with increasingly stringent regulatory mandates to reduce emissions across range of pollutants; focus on near zero emissions	Regulatory mandates to reduce emissions; focus on near zero emissions, new IGCC, and advanced coal combustion	Low environmental awareness, coupled with little or no IGCC or advanced coal combustion decreases focus on emissions reduction	Focus on new IGCC and advanced coal combustion
Technology R&D Gaps: For each scenario, these represent the critical technology R&D needs in the area of emission control for fossil power plants.	For coal plants, RD&D methods to: Reduce mercury emissions from coal-fired power generation by 95 percent, and reduce costs — Very critical	Very critical	Very critical	Very critical
	Reduce SO_x and NO_x emissions from coal-fired power generation to near zero levels, and reduce costs — Very critical	Very critical	Important	Very critical
	Enable > 90% utilization of combustion products from coal-based power generation — Very critical	Very critical	Important	Very critical
	Address water use limitations — Very critical	Very critical	Important	Very critical
	Ensure consistently low particulate emissions over all load levels — Important	Important	Important	Important
	For combustion turbine plants, develop fuel flexible dry low NO_x combustors and optimize their operation; address syngas impact on SCR catalyst; improve turndown with low emissions — Important	Very critical	Important	Very critical

Legend:
Very critical (solid red arrow)
Critical (dashed orange arrow)
Important (dashed blue arrow)

Arrows indicate that the R&D need applies to *more than one scenario*

Figure 5-6
EPRI Scenario and Technology Development Matrix for Emissions Control of Fossil Power Plants

Environmental Science and Technology

Overview

In this century, demand for electricity will increase, driven by such powerful forces as population growth, urbanization, expanding global commerce, and the imperative to improve quality of life. Regardless of the scenario, significant new generation capacity will be needed to meet this growth. From an environmental and health perspective, this is good news, because societies that derive a greater portion of their energy from electricity have both greater economic output (and thereby are able to provide better healthcare, for example) and lower emissions per unit of energy consumed.

Nevertheless, more fundamental research is necessary to improve understanding of the environmental risks and benefits associated with this expanded electricity generation and use. This information is critical to those in the electricity business, policymakers who influence technology choices and assess risks, and the public, which is both a consumer of electricity and part of the global environmental fabric. The most critical issues needing further research are: better understanding of the potential costs and benefits of climate change policy proposals; the importance of water availability and quality for development, including electricity generation; the health impacts of air pollutants, such as fine particulates; and whether magnetic fields from T&D lines lead to adverse health effects. In parallel, improved methods of conducting lifecycle and total ecosystem approaches are needed to effectively manage complex environmental issues in the future.

Effective communication to a broad range of stakeholders is particularly important in the area of environmental science and technology. The issues and concerns in this area are not simple, and explanation of them is often challenging. Yet the need for this communication is acute, and will continue to grow, as public perception of some issues is not consistent with scientific results.

Emerging Environmental and Human Health Issues

Environmental and human health issues will be particularly important as the electricity enterprise evolves to deploy new generation technologies such as distributed energy resources (DER), integrated gasification combined-cycle (IGCC) with carbon capture and sequestration, advanced nuclear power, renewables such as photovoltaics, and hydrogen-based energy technologies, such as fuel cells. In each case, unanticipated potential impacts on the environment or human health are possible via effects on air quality, water quality, magnetic fields (EMF), land use, and others.

For example, new issues are likely to emerge when examining whether stored carbon dioxide can permanently remain in saline aquifers or other geological repositories. Large-scale deployment of distributed generation technologies such as microturbines may have unanticipated air quality, noise, or EMF impacts compared with central-station generation and transmission/distribution to consumers. Wide-scale application of renewables, such as wind, biomass and solar, may have land-use impacts or change local microclimates. Further in the future, migration to a hydrogen-electric economy may introduce unanticipated potential impacts of hydrogen transport and use (see Figure 5-7).

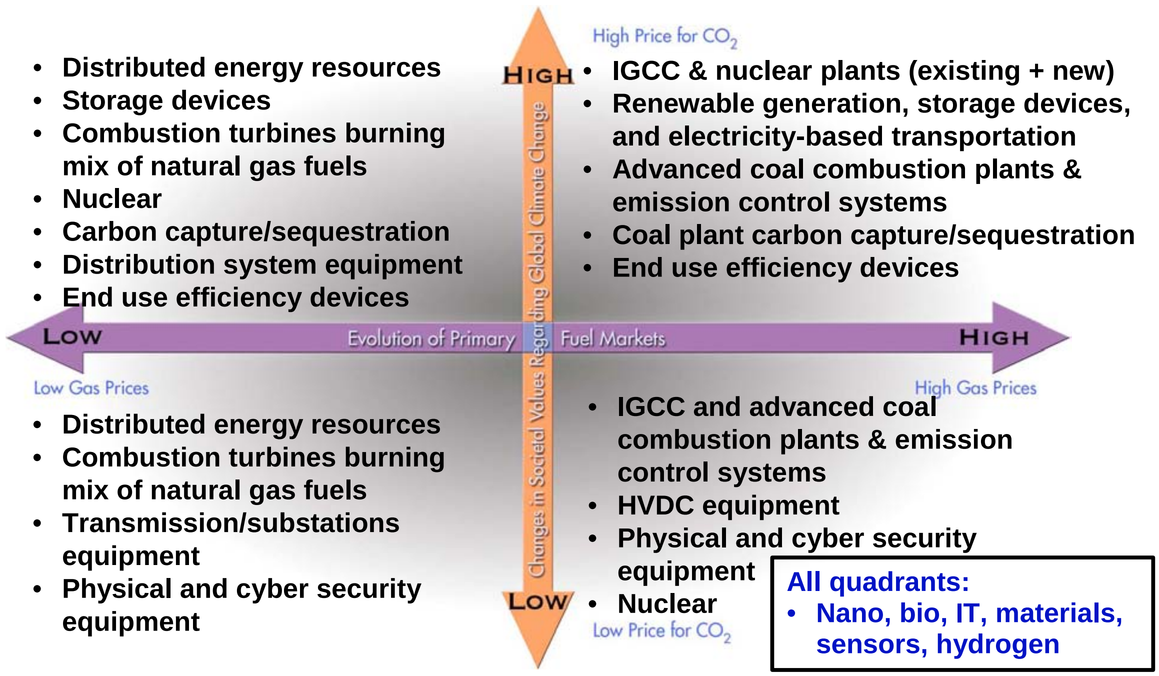

Figure 5-7
Assessing the potential environmental and human health impacts of these emerging technologies in each scenario is a high priority.

The goal will be to identify and resolve environmental and human health issues and potential impacts at an early stage of technology development, making it possible to minimize potentially significant impacts in the technology design phase, rather than after deployment. R&D needs in this area include the following:

- Understanding the potential local and regional environmental and human health effects associated with emerging approaches to electrification (e.g., distributed energy resources and renewables versus central station coal and nuclear)
- Identifying and characterizing potential environmental and human health impacts of advanced fossil generation (e.g., IGCC with carbon capture and sequestration, hydrogen production from fossil fuels, and advanced coal cycles)
- Identifying and characterizing the environmental and human health implications of the "hydrogen economy" (e.g., transportation and storage risks, waste products produced, and issues associated with hydrogen production)

Global Climate Policy Costs and Benefits

The global climate change issue is motivated by a growing consensus that human activities are contributing to the buildup of carbon dioxide (CO_2) and other greenhouse gases (GHGs) in the atmosphere, and that this accumulation of GHGs will cause adverse changes in temperature, precipitation, and other important climate variables. As a result, policy proposals are being considered at many levels of jurisdiction.

International efforts to mitigate climate change are based primarily on a treaty – the United Nations Framework Convention on Climate Change (UNFCCC) – signed by 154 countries at the 1992 Earth Summit. The ultimate goal of the UNFCCC is "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." To date, the Conference of the Parties (COP) to the UNFCCC has not determined a specific stabilization target, but actions to reduce emissions of CO_2 and five other GHGs – methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride (SF_6) – are proceeding through a variety of private-sector efforts and government programs.

The Kyoto Protocol[17] entered into force on February 16, 2005. Domestic actions are becoming increasingly frequent in developed countries that signed the Protocol (as well as others who did not sign but are involved in voluntary programs) and are likely to continue to grow in the future. These actions include a broad array of activities such as the following:

- In the United States, the Bush Administration adopted a policy to slow, then stop, then reverse the growth in emissions via reductions in the intensity of GHG emissions relative to economic output. Congressional bills are being proposed at a rapid and accelerating rate. Regional and state proposals are proliferating.
- The European Union Emission Trading Scheme and the Clean Development Mechanism is an operating emissions trading system intended to facilitate achievement of the emission reductions needed to meet national commitments that would pertain under the Kyoto Protocol.
- Worldwide investments in project-based emission reductions[18] have more than doubled over the last three years, exceeding $660 million in 2005; that number is expected to continue rising over time.

Stabilizing atmospheric greenhouse gas concentrations may be one of the grand challenges of the 21st century, requiring investments and innovations far beyond those associated with any other environmental issue. Addressing this challenge requires efforts in three areas: 1) climate policy, 2) technology policy, and 3) company policy.

[17] The Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC) sets emission reduction commitments for Annex B countries (developed countries and those in transition to market economies). The Protocol has an overall goal of reducing average annual Annex B emissions in the first commitment period (2008–2012) by at least 5% below 1990 levels. Emission reduction targets are differentiated for the Annex B countries, with some committing to larger cuts than the average of 5% and some committing to smaller cuts (or even small increases).

[18] The term *project-based emission reductions* refers primarily to two mechanisms under the Kyoto Protocol through which investments are used to fund projects that result in lowering emissions of greenhouse gases, and for which the investor receives reduction credits in return. Projects funded in developed countries are carried out through a mechanism known as Joint Implementation, whereas projects funded in developing countries are carried out through the Clean Development Mechanism.

Climate Policy

The overall costs of CO_2 stabilization have been estimated to be on the order of trillions of dollars, depending on the ultimate concentration ceiling and the details of implementation. Given the enormous stakes – and the substantial uncertainties associated with climate change predictions, implementation issues, and accompanying impacts – there is considerable value in providing policymakers with crucial information to help them make environmentally effective and economically efficient climate policy decisions. The following capabilities are needed to enable analysis of specific policies that are proposed:

- The ability to examine policy implementation issues such as the relative advantages of market mechanisms (e.g., cap and trade and carbon taxes), command and control, complete versus partial coverage of sectors of the economy, and point of regulation (i.e., upstream versus downstream)
- The means to examine the sensitivity of overall near-term costs to the general architecture of climate policy and implementation details.
- Capability to better understand the longer-term determinants of the costs of meeting climate goals.
- Information on potential impacts of climate change, the costs of adaptation, and the interaction between mitigation and adaptation policies. This includes an understanding of how changes in key climate variables (e.g., temperature, precipitation) might affect the physical and natural systems of interest. These include market impacts such as those associated with agriculture, coastal property, timber, and water resources, as well as effects that are not as easily quantified in monetary terms such as impacts on human health and ecosystems.
- The means to perform integrated assessments that combine information on costs and avoided harmful impacts.

Technology Policy

Technological advances can play a critical role in managing the costs of compliance with climate policies. Stakeholders need to develop technology policy and establish institutions that encourage and provide incentives for the development of technologies to address climate change, so they are available when needed. Informing technology development efforts requires information in the following areas:

- Continuing assessments of the potential value of technological advances
- Improved understanding of the process of technical change
- Further examination of the diffusion of technology across nations
- Innovative research into the structure of public-private programs for creating technology advances

Company Policy

The economic costs of global climate policy proposals are potentially unprecedented in size and reach, and are likely to affect all segments of the electricity enterprise. The climate policy context may change in the future, with the possibility of mandatory emission reductions and technology R&D policies. In light of evolving climate policies and other uncertainties, companies need to be able to evaluate investment decisions to support corporate strategies. To anticipate companies' evolving needs, R&D will be needed in the following areas:

- Develop methods to help companies evaluate investments in light of climate policies
- Provide information on non-traditional emission reduction opportunities (e.g., forestry, various carbon markets)

Water Quality and Availability

Assuring water availability, quality, and security in an environmentally acceptable manner has far-reaching implications for economic development, environmental policy, human health, and land use within thousands of watersheds. Addressing tomorrow's water requirements will be a complex challenge, involving numerous stakeholders; and interconnected ecological, legal, technical, and financial issues. The electric power industry is an important industry in this water challenge, accounting for approximately 40 percent of all freshwater use in the U.S. (although consumption is much less because much of the water is used for cooling and returned to the water body). In this context, two water issues are paramount: 1) water body impairments, and 2) potential water shortages.

With regard to water body impairments, in 2002, individual states reported over 52,000 impairments affecting approximately 22,000 water bodies that need to be cleaned up. EPA has joined these states in setting a 2012 goal to restore 25 percent of these water bodies and a 2015 goal to restore 50 percent. Total maximum daily load (TMDL) studies, the mechanism to establish the methods to restore watersheds, will affect water, land, and air policy decisions with a very large potential economic impact. The U.S. Environmental Protection Agency (EPA) has endorsed a watershed approach for integrated management and protection of rivers, lakes, estuaries, and other water bodies. The watershed approach utilizes a community-based, consensus-building framework for decision making, instead of the traditional agency-based command-and-control approach. The watershed approach to permitting provides a process for considering all stressors within a hydrologically defined drainage basin, rather than addressing individual pollutant sources on a discharge-by-discharge basis.

R&D is needed to deliver credible scientific information, practical guidance, and proven decision-support tools and technology assessments. This R&D will help utilities, regulators, and other stakeholders develop and implement effective strategies for watershed assessment and management, water resource sustainability, water quality trading, TMDL analysis, ecosystem protection, individual power plant water use, and condenser and cooling system design and operation.

More-stringent water quality criteria could have similar effects. Government officials, utilities, and other stakeholders need better scientific data and improved analytical capabilities to support the design and implementation of resource-efficient strategies for mitigating the risks associated with mercury and other chemicals (e.g., selenium, aluminum, arsenic, and ammoniated discharges) in aquatic environments. In addition, scientifically sound and cost-effective methods are needed to establish water quality criteria and discharge permit limits that reflect site-specific conditions.

A second major developing issue for the United States is sustainability of water resources. According to a 2003 Government Accountability Office (GAO) survey, 36 states responded that they anticipate water supply shortages in the next ten years under average precipitation conditions. And these states are not limited to the arid and semi-arid West and Southwest, but occur throughout the United States. Vulnerability will increase over the next quarter of a century as a result of greater demands for fresh water associated with population growth. Climate change and growing concerns about environmental protection may exacerbate the situation. Almost all thermoelectric plants and all hydroelectric plants need sufficient water supplies to meet their generating demands. Both existing and future plants are vulnerable to water shortages. Utilities need to understand their vulnerabilities to water shortages as well as strategies for reducing those vulnerabilities.

Air Quality Impacts on Human Health

The human health and environmental impacts of fine particulate matter and other air pollutants have been examined for decades, but scientists are only now beginning to understand the actual causative agents and physiological mechanisms involved. Using epidemiology, toxicology, and exposure assessment, together with sophisticated monitoring systems, scientists are beginning to identify the specific components of air particles that are most responsible for observed health effects.

This is one of the critical areas where scientific research can play a pivotal role is providing improved understanding, which allows policymakers to focus on controlling emissions from those sources that most contribute to health effects. This results in more effective policies for protecting public health. A prime example today is fine particulate matter (PM), which has been shown to be associated with negative health effects. Among the major components of PM are nitrates and sulfates, which are formed as a result of sulfur dioxide (SO_2) and nitrogen oxides (NO_x) emissions from power plants, vehicles, and other sources. However, fine PM is composed of many organic and inorganic compounds and metals. Recent research is finding that the carbonaceous fraction of PM may pose the greatest health risks, not sulfates or nitrates (the predominant component of PM). Thus, controlling sulfates and nitrates may not result in anticipated positive health benefits if these pollutants alone are controlled.

Current standards focus upon the total mass of PM in the atmosphere and do not consider potential differences in component toxicity. One possible means to address this issue is to not regulate PM on a total basis but rather on a component basis. In this way, the most toxic components can be targeted for control and thus protect public health. Decision makers, including EPA and state agencies, need the best health- and science-based information available to ensure that air quality standards are implemented in a way that maximizes their value to society.

R&D needs include resolving major issues related to particulate matter formation, including secondary organic aerosols; applying epidemiology, toxicology, and exposure assessments through comprehensive studies to focus on components of greatest health risk for control; developing greater understanding of dose-response relationships for toxic compounds to determine safe levels for human exposure; and improving risk assessment methodologies to determine what substances are most critical for reducing exposure and which are less critical.

Magnetic Field Impact on Human Health

Electric T&D systems generate low-level magnetic fields (EMF), which continue to be scrutinized in relation to effects such as childhood leukemia and various forms of cancer. The National Institute of Environmental Health Sciences (NIEHS), the United Kingdom’s National Radiological Protection Board (NRPB; now the Radiation Protection Division of the Health Protection Agency), the International Commission on Non-Ionizing Radiation Protection (ICNIRP), and the California Department of Health Services (CDHS) have recently conducted health risk evaluations. All of these evaluations have concluded that exposure to magnetic fields is associated with childhood leukemia risk, and some have raised issues concerning adult leukemia, miscarriage, and neurodegenerative disease. Moreover, based on childhood leukemia studies, the International Agency for Research on Cancer (IARC) has classified EMF as a possible human carcinogen. Several organizations have set guidelines for limiting worker and public exposure to EMF and contact current.

To meet increasing demand for electricity, new transmission lines and substations will need to be constructed, and the distribution system will require a substantial upgrade. The start of new construction in several states has already raised public concern about EMF. As power grid expansion continues (with over 10,000 miles of new transmission lines carrying 230 kV and above planned through 2013) and distributed generation facilities are introduced, public concern can be expected to rise.

The issue with the association between EMF and childhood leukemia is that exposure studies to animals and cells at high field strengths show no biological response. This presents a conundrum to the research community. One emerging hypothesis regarding the potential link between childhood leukemia and magnetic fields is “contact current” (e.g., touching a metallic surface with a low electrical potential, causing a small current to flow through the child’s body, including the bone marrow, that reaches ground via another conductive medium such as the drain in a filled bathtub). Another hypothesis is selection bias in studies showing a positive association between field strength and health effects. (Selection bias refers to how the two sets of individuals studied were selected and whether they were in fact comparable.) Research is needed to resolve uncertainties about childhood leukemia and other health endpoints of potential concern. Critical needs include the following:

- Improving scientific understanding of the association between EMF and childhood leukemia and other health outcomes, which will involve further study of the contact current hypothesis; more laboratory studies of environmental leukemogenesis; and basic research on the interaction between electricity and blood forming components

- Better understanding of the potential EMF ramifications of the future electricity infrastructure

Lifecycle Analysis

One key approach that is likely to greatly influence how environmental issues are managed in the future is lifecycle analysis. This approach considers not just environmental impacts during the operating life of a technology or material, but also its impacts during manufacture before it begins operation and its impacts upon disposal or recycling. The American Society of Testing Materials (ASTM) is beginning to develop a methodology that can be used to help characterize the lifecycle impacts of various electric power generation options.

A related approach to lifecycle analysis is to adopt a total ecosystem approach to the examination of emission sources, transport mechanisms, geophysical cycling, and toxicology of substances. Mercury is an excellent example of the complexity of managing an emission stream. Mercury entering lakes – by direct deposition from the atmosphere or via terrestrial runoff – typically includes elemental mercury and oxidized mercury. But it is the compound called monomethylmercury, CH_3Hg, which is of concern to human health. This compound may be produced when anaerobic bacteria in the water and sediments methylate oxidized mercury through a metabolic process. Plankton and other organisms bioaccumulate the CH_3Hg, passing it up the food chain to fish, where it may concentrate to levels of concern to human health. Studying how mercury is transformed as it moves through the ecosystem once it leaves a particular source such as a power plant is critical to determining how interventions, such as controls on emissions, would benefit human health and the environment.

Lifecycle and total ecosystem analyses will be critical to placing environmental consequences in perspective. They will also help provide additional information to assess total costs (including environmental externalities) and public acceptance. Hence, lifecycle and total ecosystem analysis methods are needed to critically assess the lifecycle costs and total ecosystem impacts of power industry generating technologies, products in use (such as chemically treated wood distribution poles), and various emission streams.

Conclusions

Clearly, all of the environmental science and technology issues discussed above will be particularly relevant in the two scenarios with high environmental awareness (“Double Whammy” and “Biting the Bullet”). Further, each new technology that is adopted in each of these scenarios (e.g., distributed energy resources, renewables, electric transportation, and energy storage) will pose new challenges to evaluate potential environmental and human health effects.

Advances in new central station generation may pose environmental risks as well. In the two scenarios with high natural gas prices, for example (“Double Whammy” and “Digging in our Heels”), adoption of integrated gasification combined cycle (IGCC) and advanced pulverized coal power generation will require close scrutiny of effluent streams and potential impacts (see Figure 5-8).

"Supply to the Rescue," with its reliance on expansion of central station power generation and the transmission system, poses significant environmental challenges as well. Water quality and availability, air quality impacts, and EMF impacts remain important issues in this scenario.

The importance (and need for improved methods) of effectively communicating the complex interactions of power generation, delivery, and use with environmental and human health effects remains a key task across all four scenarios.

Key R&D Topics

Following is a list of the key R&D topics for the area of environmental science and technology:

- Develop/apply tools to assess costs and benefits of climate policies to utility industry and member companies
- Resolve the uncertainty of the association between EMF and childhood leukemia
- Establish scientific basis for development of component-based fine particulate matter standard
- Address water treatment and management needs, including scientific support for anticipated new effluent guidelines and new water conserving technologies
- Address environmental impacts of new advanced coal plants such as IGCC as well as distributed generation plants
- Develop tools for component lifecycle and total ecosystem analysis of emissions
- Develop models for optimization of strategies that address air-water-climate interactions
- Explore nanotechnology for treatment of low-level liquid waste streams

Scenario	**"Biting the Bullet"** High CO_2 prices; Low gas prices	**"Double Whammy"** High CO_2 prices; High gas prices	**"Supply to the Rescue"** Low gas prices; Low CO_2 prices	**"Digging in Our Heels"** High gas prices; Low CO_2 prices
Overview and drivers of technology R&D	Environmental protection is a top priority; low gas prices increase options	Environmental protection is a top priority; high gas prices require innovative science & technology solutions	Environmental R&D is needed to mitigate impact of expanded central station power generation and delivery system	Environmental protection remains important, but is not a top priority
Technology R&D Gaps: For each scenario, these represent the critical technology R&D needs in the area of environmental science and technology.	Environmental and human health effects of emerging technologies (e.g., DER, storage, CTs on mix of fuels)	(e.g., IGCC, Advanced PC, nuclear, renewables)	(e.g., DER, CTs on mix of fuels)	(e.g., IGCC, advanced PC, HVDC)
	Develop/apply tools to assess costs and benefits of climate policies			
Legend: Very critical; Critical; Important. Arrows indicate that the R&D need applies to *more than one scenario*	Develop information, tools, and techniques to guide strategies for watershed management and reduce vulnerabilities to water shortages			
	Assess safe levels & risk to human health of particulate matter on component level			
	Resolve EMF/leukemia uncertainty			
	Develop tools for component lifecycle and total ecosystem analysis of emissions			
	Develop models to optimize strategies for air-water-climate interactions			
	Explore nanotechnology waste treatment			

Figure 5-8
EPRI Scenario and Technology Development Matrix for Environmental Science and Technology

6
TECHNOLOGY R&D NEEDS: POWER DELIVERY

This section covers technology R&D needs in the power delivery area. It addresses the following topics:

- Transmission and substations
- Grid operations and resource planning
- Distribution systems
- Power quality
- Physical and cyber security

Transmission and Substations

Overview

The high voltage transmission system is the “backbone” of the power delivery system in North America. It transmits very large amounts of electric energy between multiple regions and sub-regions. Transmission system equipment fails and causes power outages much less frequently than distribution equipment. But when transmission system equipment does fail, many more consumers are affected, and outage costs can be much higher, compared to the impact of a distribution equipment-related outage. This fact, combined with the high cost per mile or piece of transmission equipment underlines the critical nature of properly maintaining this asset under any scenario.

Historically, the transmission system was expanded in advance of needs via a highly regulated process. Changes to this process in recent decades have led to reduced transmission expansion, which bottomed out in the late 1990s and early 2000s. Transmission expansion is now recovering, but vigilance is required in the future, especially in scenarios where rapid load growth may place strain on the transmission system without proper advance planning (e.g., that may occur in the “Supply to the Rescue” scenario). Another key factor is the aging of this infrastructure. Most transmission lines and substations were constructed over 40 years ago based on technology of the 1950s. Superimposed on this is the changing mission of the transmission system. Originally constructed to serve local load, the transmission system is now being pressed into service for a bustling wholesale power market in which wholesale power is bought and sold across wide distances. These factors reinforce the need to focus on maintaining and upgrading the North American transmission system.

Diagnostics, Maintenance, and Life Extension

Technology R&D needs in the area of diagnostics, maintenance, and life extension include overall substation maintenance management; transformer and overhead line life management; and safe maintenance work practices. These fundamental needs, which relate to the huge existing infrastructure, are applicable across most scenarios.

Substation Maintenance Management. Substations pose a range of complex and interrelated issues, including an aging infrastructure, maintenance and operation budget limitations, and demand for high reliability. To address these issues, maintenance optimization is a key enabling technology. Information and methodologies are needed to help maintenance and asset managers direct their limited resources to best achieve business goals with respect to substations. Development and demonstration of substation information, decision support tools, and data analysis techniques will provide the following benefits:

- Reduce maintenance costs
- Extend equipment life
- Guide investment decisions
- Quantify benefits
- Improve equipment performance assessment
- Forecast equipment reliability
- Mitigate the impact of an aging infrastructure population – widely seen as "asset walls"
- Establish safer operating practices

Transformer and Overhead Line Life Management. Many utility power transformers and load tap changers have been in the field beyond their 40-year design life. Managing this aging population requires advances in diagnostics, monitoring, on-line condition assessment, and life extension techniques. New techniques are needed to improve the level of information available to owner/operators of these expensive assets (e.g., via improved data mining techniques), enabling better investment decision making, increased reliability, reduced failures, safer operating practices, reduced maintenance costs, and extended life on transformers. Understanding the effective age of transformers will allow for their optimal utilization, including improving the maintenance approach, operating above nameplate ratings, or using the transformer as a spare. Initial work is needed in the areas of transformer end-of-life and condition assessment, transformer life extension, and geomagnetically induced currents.

Similar work is needed for overhead transmission. Overhead transmission line owners and providers of overhead transmission services need tools and techniques to aid the following:

- Identifying high risk components prior to failure
- Assessing populations of components to determine whether to extend life, refurbish or replace
- Developing new, or refining existing, inspection and assessment processes

- Increasing understanding of component aging and life expectancy, resulting in better application and more durable products
- Educating both engineering staff and field personnel

This R&D will help lower operation and maintenance costs and extend life of overhead transmission line facilities. It will also enable members to select appropriate components and apply them correctly when designing new facilities or refurbishing existing facilities.

Safe Maintenance Work Practices. Safety of workers is always an important factor in utility operations. Proper and well conceived procedures for work tasks with strong emphasis on safety will provide a high return on investment through improved worker productivity and safety, and an increase in system reliability. Research has shown that accidents can be prevented by developing procedures and controls that effectively set up barriers to block dangers resulting from human errors and other causes of incidents. As no barriers are perfect, they contain “holes” through which errors can propagate. Incidents occur when these “holes” line up and fail to prevent propagation of errors (see Figure 6-1). Technology R&D is needed to understand how accidents happen and how they can be avoided or prevented, with special emphasis on switching activities in the power system.

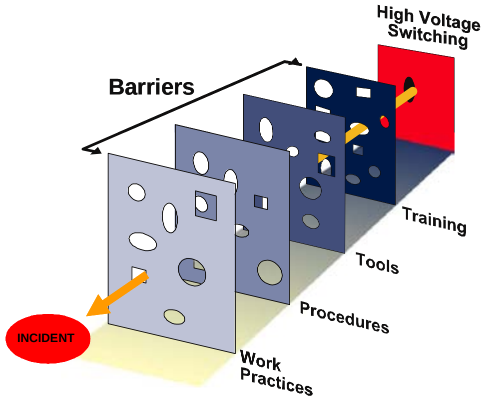

Figure 6-1
An Approach to Improving Work Practice Safety

Deregulation and economic realities of today’s electric utility business are forcing energy companies to ensure that transmission and distribution (T&D) lines remain in service every day of the year. Increasingly, transmission owners are turning to live-line working techniques as standard practice. R&D is needed to help overhead transmission owners and maintenance service providers improve transmission performance and enhance reliability by supporting worker safety when conducting live-line and de-energized maintenance on overhead transmission equipment. Overall, this work will help members increase transmission circuit reliability/availability, increase worker safety, and decrease maintenance costs by developing and improving methods, tools, equipment, and training materials for maintenance on energized and de-energized transmission lines.

Technology R&D that Addresses Environmental Concerns

Technology R&D that addresses environmental issues, as well as a heightened environmental awareness addresses both the “Biting the Bullet” and “Double Whammy” scenarios. With regards to transmission and substations, these issues include reduction of sulfur hexafluoride (SF_6) released to the environment, information on magnetic fields (EMF), compaction and multiple uses of rights-of-way, and reducing costs of underground transmission.

Sulfur Hexafluoride Management. Sulfur hexafluoride (SF_6) is used as insulation for a range of substation equipment (e.g., breakers). It is a powerful greenhouse gas with a 100-year global warming potential of 23,900 (i.e., 23,900 times more powerful than carbon dioxide). SF_6 is a costly gas (currently in the range of $4–$10 per pound) and poses potential heath hazards. To address this hazard, the following R&D is needed:

- Research and utility guidelines on SF_6 and the environment – and possible SF_6 replacements
- Steering of development and field trials of new SF_6 leak detection cameras
- Development of practical guides and training on SF_6 handling practices
- Research on condition monitoring of SF_6-insulated equipment
- Research on gas-insulated substations

This work would provide the following benefits:

- Significantly improve the performance of SF_6-insulated equipment
- Provide tools to extend and estimate equipment life
- Reduce maintenance and operating costs of SF_6 equipment
- Appropriately manage SF_6 environmentally, and hence protecting the significant investment in SF_6-insulated equipment
- Accurately track the development of SF_6 replacements and SF_6 policy issues to provide appropriate and timely guidance on the future of SF_6

Magnetic Field Management. Proper management of magnetic fields remains a concern, particularly for underground transmission, because of its close proximity to potential human contact. Field management of magnetic fields generated by underground transmission can be provided via several technical means. However, stakeholders need increased certainty on the effectiveness of these measures and how they perform over the long term. Hence, R&D is needed to provide the necessary tools to evaluate the effectiveness of magnetic field management techniques such as plating, metal enclosures, metal reinforced concrete, or pipes. Utilities also need to be able to determine the impact of magnetic field mitigation techniques on cable ratings. For more information on magnetic field issues, refer to the section on environmental science and technology.

Compaction and Multiple Uses of Rights-of-Way. Transmission line owners are under increasing pressure to allow other systems and structures to share existing rights-of-way (e.g., pipelines, cellular phone repeater stations, fiber optic repeaters, parking lots, and distribution systems). R&D is needed to investigate this issue from a range of perspectives, including the influence of steady-state conditions, transient conditions, fault conditions, installation, and the influence of maintenance operations on both the transmission line and the cohabiting systems. Guidance is also needed on design and maintenance rules for these systems.

Similarly, compaction of overhead lines lowers capital and maintenance costs, reduces line losses, and reduces EMF at ground level. However, disadvantages include higher voltage gradients on conductors and insulators resulting in higher audible noise, radio interference, increased hardware corona, and aging of composite materials. Decreased lightning performance, higher fatality rates of large birds, and live line maintenance practices are also concerns together with mechanical issues such as conductor galloping and wind loadings. Hence, R&D is needed to address these concerns.

Reducing the Costs of Underground Transmission. In both scenarios with high environmental awareness, demands for underground transmission are likely to increase due to concerns of aesthetics. Underground transmission provides other benefits, including improved reliability during exposure to extreme elements (e.g., hurricanes and ice storms). In some cases, urban congestion requires underground solutions. But underground transmission is much more costly than its overhead counterpart, and maintenance is much more difficult. These challenges are complicated by the fact that different technologies are used for underground transmission, compared to overhead transmission, including significant use of insulation. R&D is needed to reduce the cost of new construction, decrease maintenance costs, increase the reliability of high-voltage and extra-high-voltage cable systems, and mitigate the environmental impact of operating paper-fluid dielectric cable systems.

Technology R&D to Increase Power Flow in Transmission Circuits

Deregulation and shifting power flows are forcing the power grid to operate in ways it was never intended. Consequently, the North American Electric Reliability Council (NERC) has indicated that about 1500 desired power transactions could not be implemented in 2005 due to transmission bottlenecks. This trend, along with a trend of increased electric power demand, has pushed the capacity of many transmission circuits to their design limits. Fortunately, some transmission circuits have greater capacity than the design specifications, and this extra hidden capacity can be utilized reliably and safely with the proper technology. To do this, various advances in materials, device technology, and techniques are needed. This ability to "do more with less" clearly supports the demands of "Supply to the Rescue" and helps meet the complex needs in "Double Whammy," where efficient use of all resources is critical.

Power Electronics Controllers. Power electronics controllers are revolutionizing the way power is transmitted and are taking a giant step toward providing the robust power infrastructure that is now needed. These controllers increase the power carrying capacity of individual transmission lines and improve overall system reliability by reacting almost instantaneously to disturbances. Electromechanical controllers are too slow to govern the flow of alternating current in real-time, resulting in loop flows and bottlenecks. By acting quickly enough to provide such control, power electronics controllers can increase or decrease power flow on particular lines, alleviating transmission system congestion. In addition, these controllers can enhance system reliability by counteracting transient disturbances almost instantaneously, optimally directing power flow, and providing wide-area voltage support, allowing transmission lines to be loaded closer to their inherent thermal limits. If power electronics controllers are extensively deployed throughout the North American grid, system operators will essentially be able to dispatch transmission capacity across the continent, facilitating open access.

In many instances, power electronics controllers can increase power transfer capability by up to 50 percent and, by eliminating power bottlenecks, extend the market reach of competitive generation. While useful in all scenarios, capabilities like these are particularly crucial in the "Supply to the Rescue" scenario. In economic terms, this boost in power supply translates into less construction, reduced capital expenditures, rapid payback of capital, and in many cases, an alternative to the growing difficulty of siting new lines. These benefits are also especially helpful to support the "Double Whammy" scenario, in which efficient use of existing transmission assets is paramount.

Next Generation Controllers. After nearly 20 years of R&D, three generations of these controllers – primarily based on silicon – have entered service. However, at this time, power electronics devices are individually controlled. Achieving a higher available transfer capability (ATC) for a transmission system calls for consideration of power electronics control from a systems point of view. In other words, new system control logic is needed that allows the integrated control of multiple power electronics devices to provide maximal ATCs while maintaining system dynamic security, including voltage security.

To hasten widespread use of electronic controllers on high-voltage power systems, a major technological breakthrough is needed. Power electronics devices based on materials other than silicon may provide that breakthrough. At this time, the most promising new materials for power electronics are silicon carbide (SiC) and gallium nitride (GaN). This new technology is also expected to substantially reduce the cost of alternating current/direct current (AC/DC) converters, enabling interconnections between asynchronous power systems and long-distance, high-voltage DC transmission. What's more, once these devices are in mass production, they promise to reduce the costs of power electronics devices.

In addition to advancements in materials, practical cost-effective development and deployment of post-silicon power electronics will also include efforts in two areas: 1) development and deployment of new switching devices, including insulated gate bipolar transistors (IGBTs) and integrated gate-commutated thyristors (IGCTs), and 2) development and application of new structural concepts for new power circuits. The latter area involves simplification of the converter and associated magnetic structure, and directly interfacing with the controlled transmission (e.g., "transformerless" controllers).

Voltage and Current Upgrades and Power Flow Management. Power flow in existing transmission circuits can also be increased via various techniques of current upgrading, voltage upgrading, and power flow management. For example, a utility can increase the power capacity of an existing transmission line by raising its voltage. By not making any major change to the existing line and by using the existing right-of-way, the utility is able to raise the power capacity of a transmission line quickly without undergoing an extensive environmental review. By using mostly the materials on the existing line, the power utility can save capital cost compared to building a new line. However, RD&D is needed to address important considerations when such upgrading is undertaken.

High-Temperature Conductors. In areas of transmission bottlenecks, retrofit of high-temperature conductors may be a viable way to increase power flow. Existing overhead conductors cannot operate over a temperature of 200°F/93°C. However, emerging alloys such as aluminum zirconium can operate at temperatures of 356°F/180°C or even 446°F/230°C. Normally only practical at voltages of 230 kV and below (when thermal capacity is the limiting factor), these high-temperature conductors must undergo demonstration in various applications to prove their viability.

High-Voltage Direct Current (HVDC) Systems

Compared to AC overhead lines, high-voltage DC (HVDC) systems at +/-800 kV can provide more economical means of transferring power from generation sources to load centers over distances longer than 800 km. HVDC thus helps utilities meet load demand with lower investment cost. HVDC lines also enhance grid reliability. Because HVDC systems allow full control of power flow and enhanced AC system stability, they foster improved reliability of the grid, which in turn will reduce the downtime of the total system. HVDC systems enable frequency control following loss of generation, enable voltage stability control, provide emergency power and black start during grid restoration, and provide power oscillation damping.

These advantages make HVDC an ideal technology for “Digging in our Heels,” in which long distance transmission lines will be needed to bring power from new remote coal-fired plants to load centers. Similarly in “Double Whammy,” construction of new remote nuclear power plants will require long distance transmission of large amounts of power. Any large-scale use of DC transmission, which must coexist with the predominantly AC current transmission system, will present challenges in both power system planning and operations.

Many HVDC systems have been in operation around the world up to voltage levels of +/-600 kV. However, construction of HVDC systems at voltage levels of +/-800 kV and above creates a need for additional research to develop various components to operate at these UHV levels. Testing and demonstration is needed of conductor bundles, insulators, and cables for operation of HVDC at +/-800 kV and above. Key issues include conductor bundle design, insulation selection, insulation coordination, transformer specification, ground electrode design and operation, substation and converter design and operation, power tap-off techniques, telecommunications, and the impact of environmental conditions. Additional R&D needs include development of tools and techniques for operation and control, as well as hotline maintenance, of these systems.

Conclusions

The broad scope, enormous embedded value, and complexity of the wide area power system is well documented. Yet this far-flung system is aging. In the face of increasing stress on this infrastructure, the strain is starting to show in a growing number of outages. Even under today's conditions (some of which are indicative of the "Digging in our Heels" scenario), the needed enhancements of this great machine are acute. The situation becomes even more critical under the conditions of some of the future scenarios. Figure 6-2 shows that the increased reliance on the power delivery system under "Supply to the Rescue" and the pressure to make best use of all resources in "Biting the Bullet" and "Double Whammy" adds more constraints to a power delivery system that is already bending under the weight of twenty-first century demands.

While the technology R&D demands in this subject area are numerous, the four areas described above and summarized below are particularly noteworthy and span the range of likely challenges:

- Advances in diagnostics, maintenance, and life extension of existing transmission and substation assets, including safe maintenance work practices
- Tools and techniques for addressing environmental concerns, such as management of the highly potent greenhouse gas SF_6, reassurance regarding EMF from underground transmission, taking advantage of the benefits of multiple uses of rights-of-way, and reducing costs of underground transmission in response to growing demands for its wider use.
- Technology to increase power flow in transmission circuits, including advances in power electronics-based controllers, voltage and current upgrade techniques, power flow management, high-temperature conductors, and others
- High-voltage direct current (HVDC) lines to more economically transfer large amounts of power over long distances, while enhancing power system control.

Key R&D Topics

Following is a list of the key R&D topics for the area of transmission and substations:

- Enhance diagnostics and life extension of aging equipment (e.g., transformers)
- Develop high current, high temperature overhead transmission conductors
- Reduce cost of underground transmission
- Develop solid-state fault current limiters
- Reduce transformer cost and improve sulfur hexafluoride (SF6) circuit breakers
- Develop advanced asset management tools
- Develop high voltage alternating current (AC) and direct current (DC) lines
- Develop advanced technologies that enable superconducting substations

- Develop advanced power-electronics-based controllers (i.e., Flexible AC Transmission Systems) for management of large disturbances, including advanced dielectric materials
- Develop low-cost, reliable remote sensors in underground & overhead transmission systems
- Integrate transmission and substation advancements with IntelliGrid technologies

Scenario	**"Biting the Bullet"** High CO_2 prices; Low gas prices	**"Double Whammy"** High CO_2 prices; High gas prices	**"Supply to the Rescue"** Low gas prices; Low CO_2 prices	**"Digging in Our Heels"** High gas prices; Low CO_2 prices
Overview and drivers of technology R&D	Regulation drives need for increase in system "efficiency" and asset utilization	Market forces & regulation drive need for significant increase in system "efficiency"/asset utilization	Expand significantly due to increased reliance on power delivery system	Expand to compensate for past insufficient growth
Technology R&D Gaps: For each scenario, these represent the critical technology R&D needs in the area of transmission and substations.	Advanced maintenance, diagnostics, & life extension tools and techniques to maintain reliability (Very critical →)	Ditto, to minimize cost of transmission components (Very critical →)	Ditto, to maintain the strained power delivery system (Very critical →)	Ditto, to minimize the cost of transmission components (Critical - - →)
	Address *environmental* concerns (e.g., SF_6, underground EMF, multiple uses of rights-of-way) (Very critical →)	Address *environmental* concerns (e.g., SF_6, underground EMF, multi-use rights-of-way) (Very critical →)	Less emphasis on *environmental* concerns (SF_6, underground EMF, multi-use rights-of-way) (Critical - - →)	Less emphasis on *environmental* concerns (SF_6, underground EMF, multi-use rights-of-way) (Critical - - →)
	Increase power flow in transmission circuits (e.g., power electronics controllers, line upgrades, and high-temp conductors) to improve asset utilization (Critical - - →)	Ditto, to improve asset utilization (Very critical →)	Ditto, due to increased reliance on power delivery system (Very critical →)	Ditto, to compensate for overdue system expansion (Critical - - →)
	Develop high-voltage, direct current (HVDC) systems (Critical - - →)	To transmit power from new remote power plants (Very critical →)	(Critical - - →)	To transmit power from new remote power plants (Very critical →)
	Reduce cost of underground transmission (Critical - - →)	(Very critical →)	(Very critical →)	(Critical - - →)
	Develop advanced asset management tools (Critical - - →)	(Very critical →)	(Very critical →)	(Critical - - →)

Legend:
Very critical →
Critical - - →
Important - - →

Arrows indicate that the R&D need applies to *more than one scenario*

Figure 6-2
EPRI Scenario and Technology Development Matrix for Transmission and Substations

Grid Operations and Resource Planning

Overview

The North American power delivery system has been called the largest and most reliable machine in the world, and the U.S. National Academy of Sciences and Engineering has ranked it the top engineering achievement of the last century. Despite this achievement, planning and operating both the local and wide area power delivery system faces a number of challenges. On the front lines of these challenges are the power system operators in energy control centers across the continent. They aim to avoid power system outages that are unfortunately increasing in frequency and to rapidly restore the system when outages do occur. Their job is becoming increasingly difficult, as transmission congestion rises in constrained corridors. And the impending retirement of a large number of experienced operators/engineers and the hiring of their replacements will pose human resource limitations and training challenges. As demands on the power system increase, these operators will need to be armed with more complete information that is processed using more sophisticated tools and displayed to them using more effective visualization techniques.

Of equal importance is the role of power system planners. In the face of growing uncertainty that spans power generation, transmission congestion, wholesale power purchases, and demand response, the scope of power system planning broadens, and its importance intensifies. Hence, power system planners are becoming integrated, inter-regional resource planners. As such, they need a completely new array of techniques and tools to anticipate needs and help ensure that these needs are met. These “holistic planners” need improved models, information, visualization tools and more, to fulfill their new role.

Integrated, Inter-Regional Resource Planning Tools

While improvements in traditional planning methods that focus primarily on transmission expansion are needed, the larger need is for integrated, inter-regional resource planning. For if broad, effective planning is not implemented and periodically updated, few of the other technology R&D needs in this area can be met.

Effective integrated resource planning must lay the foundation for effectively responding to shifting regulatory requirements and address a broad range of uncertainties. Industry restructuring and open access transmission polices have already introduced many new uncertainties, including the following:

- Location and capacity of new generating units
- Location and extent of transmission congestion
- Various bidding and dispatching rules
- Amount of demand and level of demand response
- Role of markets in planning for future power system needs

Today, these uncertainties are causing power producers, transmission providers, and regional planning organizations to rethink their planning processes and to develop the tools and information that support them.

Evolving restructuring and changing regulatory requirements have also led to a patchwork quilt of organizational structures. In some parts of the country, independent system operators (ISOs) and regional transmission organizations (RTOs), under Federal Energy Regulatory Commission (FERC) jurisdiction, have been established and tasked with a key role in power system planning. In other areas, large utilities have remained vertically (or virtually) integrated and maintain this responsibility. In other parts of the country, utility entities have been unbundled. Present and all future power system planning tools and methods must be able to accommodate this fractured organizational structure, which is not likely to become homogeneous in the near future.

Effective power system planning must also result in a transmission system that accommodates shifts in the mix of existing technologies and supports a broad array of evolving beneficial technologies. For example, a shift in the mix of types of central station generation plants fundamentally impacts the transmission system. Constructing natural gas-fired power generation located relatively close to load centers (e.g., in the "Supply to the Rescue" scenario), rather than coal-based generation located more remotely, significantly changes power flow patterns and hence the demands on the transmission system. Similarly, an increase (or decrease) in renewable power generation, energy storage, distributed resources, load growth, and even demand response technologies operating on the grid (e.g., in the "Double Whammy" scenario) impacts the power flows that the transmission system must accommodate.

Hence, movement from the current scenario to any other scenario is likely to place new demands on the power delivery system. As a result, power system planners must be equipped with tools and methods that enable them to anticipate these demands and ensure that the power delivery system is ready to cope with them.

To help planners in all parts of the market address these uncertainties, improved models, information, and visualization tools are needed to support a variety of emerging planning processes. The enhanced models and information must enable better management of the uncertainties introduced by industry restructuring and open access transmission polices. Advanced planning tools must enable planners to perform power system studies that effectively consider these uncertainties. Visualization tools must allow effective display of results of numerous uncertainties, enabling planners to more easily reach consensus on improvements to the robustness of the transmission network. Such tools and methods must also provide financial benefits by helping stakeholders reduce the uncertainty in financial outcomes.

Taken together, these needs add up to a process that can be called "holistic planning" (see Figure 6-3). Effectively, the power grid must be sufficiently resilient, robust, and "healthy" to be able to accommodate whatever task it is asked to handle. This approach involves enhancing the grid in ways that serve a broader purpose, rather than simply solving a specific short-term bottleneck or other limitation.

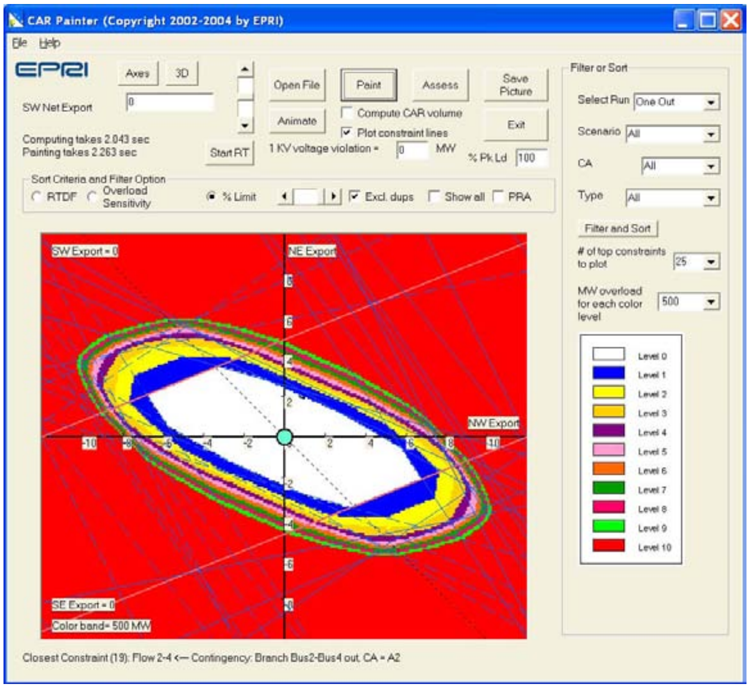

Figure 6-3
In this example of holistic transmission expansion planning, a given transmission system imposes a hard boundary (colored portions of the diagram) on the operating points of the entire power system, which are driven by demand growth, generation plants, and economic or market dispatches.

With future demands, the white region will need to be expanded by adding transmission capacity. When these capacity additions are well planned and coordinated, the entire operating space will be increased holistically to accommodate future operating points.

One R&D area that holds particular promise for addressing modeling uncertainties introduced by industry restructuring, and enabling planners to make better decisions, is enhanced probabilistic decision planning tools and methods. Today's probabilistic planning tools typically produce voluminous outputs due to the many scenarios that must be considered, and extracting meaningful results from them is a major challenge. Furthermore, the complexity of data requirements and calculations of current transmission planning tools limits the number of cases that can be practically run and the number of uncertainties that can be represented. In addition, planners accustomed to seeing deterministic results have difficulty interpreting the numerous cases usually involved in probabilistic planning. Finally, in the restructured environment, planning of transmission systems increasingly relies on group processes that bring together representatives of many stakeholders, including power producers, transmission providers, grid operators, marketers, regulators, consumers, and the public at large. These challenges require development of new tools for data management, modeling, analysis, and visualization that can support the complexities of probabilistic planning in a public process.

At the same time, in order to provide the market signals for investors to build new transmission projects, where the market needs them, an online congestion monitoring system is needed. Community Activity Room (CAR) technology can provide the foundation for development of a prototype North American transmission "traffic control center." Aided by the high-speed data network connecting the control center computers of all regional reliability authorities, this system could collect data from all regions in near real-time and display the current operating point of the entire interconnection on a "radar screen." Congestion indices can be computed in real time, and statistics of congestion at various transmission bottlenecks can be made available to all stakeholders, so that a consensus can be reached as to the optimal location of new transmission investments to enable efficient power market growth.

Local and Wide-Area Power System Operation

A broad array of challenges and resulting technology R&D needs involve the effective operation of both local and wide-area power systems. Methods are needed to better assess the current state of the local as well as wide area power system – either to anticipate problems by recognizing early symptoms or to respond to disturbances already underway. The availability of numerous condition-monitoring sensors connected to a secure communications network will be crucial for achieving a rapid assessment. Thousands of monitoring points are needed that can provide real-time data throughout the power system on a regional basis.

The first demonstration of a measuring and monitoring capability that covers a large power system has been underway in the western United States under the name Wide Area Measurement System (WAMS). WAMS is a system based on high speed monitoring of a set of measurement points by means of Phasor Measurement Units (PMUs), "concentration" of these measurements by means of Phasor Data Concentrators (PDCs), and generation of displays based on these measurements. This system is based on global positioning system (GPS) satellite communications and time-stamping of data that is collected. This system is capable of detecting and reporting phase angle swings and other critical transmission system changes over a wide geographical area. By constantly monitoring conditions throughout a wide-area network, WAMS can detect abnormal system conditions as they arise and enable mitigating action. The Bonneville Power Administration (BPA), Western Area Power Administration (WAPA), several other major energy companies including Southern California Edison, EPRI, U.S. Department of Energy, the U.S. Bureau of Reclamation, two national laboratories, and others have all participated in the development and early implementation of WAMS. In a related project called Wide Area stability and voltage Control System (WACS), BPA is demonstrating an on-line R&D project oriented towards improving Pacific AC intertie stability and transfer capability.

A major effort has been started in the Eastern Interconnection under the name Eastern Interconnection Phasor Project (EIPP). This industry-led project, supported by the U.S. Department of Energy, includes participation from manufacturers, software developers, operating/reliability organizations, academia, government, Institute of Electrical and Electronics Engineers (IEEE), other standards bodies, and more. The EIPP mission is to "create a robust, widely available, secure and accessible synchronized data measurement and communication infrastructure over the eastern interconnection with associated analysis and monitoring tools for better planning and operation and improved reliability."[19] Phase I of the project plan aims to integrate 30 or more synchronized monitors into a coherent data network. Planned applications

[19] Consortium for Electric Reliability Technology Solutions (CERTS), http://certs.lbl.gov/certs-eipp.html

include improving situational awareness, state estimation, event/disturbance analysis, and others.[20]

Expansion of these capabilities is crucial to enable implementation of a continental power grid. Reliable, real-time gathering of a range of power system parameters will enable operators to detect and counteract abnormal conditions over a wide geographic area, thus enabling the system to operate safely closer to its inherent limits. Proper R&D will enable a broader implementation of WAMS- and WACS-like systems that provide the real-time information needed for integrated control of a large, highly interconnected transmission network (see Figure 6-4).

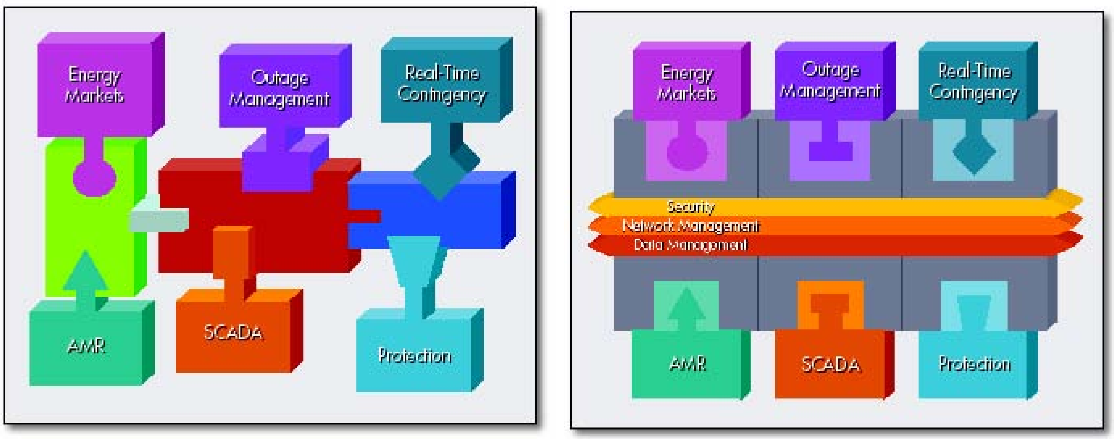

Figure 6-4
Today's intelligent systems tend to be developed in isolation and are often connected to the utility system through proprietary communication interfaces (left).

Because there is little integrative planning, systems that could benefit from common data and communications – outage management and automatic meter reading (AMR), for example – have difficulty "speaking" to each other. The IntelliGrid[SM] approach (right) defines standardized interfaces first and promotes the use of a common language; basic needs such as security and data management are built into the system from the outset. As a result, new applications can be added to the architecture more easily and effectively. Photo courtesy: *EPRI Journal*

Of course, the power delivery system does not operate in a vacuum. It is tightly coupled to the fuel supply infrastructure (e.g., natural gas pipelines and coal mining and transportation systems), the telecommunications infrastructure, and consumer facilities. Hence, effective operation (as well as planning) of the power deliver system must reflect this interdependence of the grid with these infrastructures.

[20] "Eastern Interconnection Phasor Project," Matt Donnelly, Mike Ingram, and James Richie Carroll, Proceedings of the 39th Hawaii International Conference on System Sciences – 2006, http://csdl2.computer.org/comp/proceedings/hicss/2006/2507/10/2507100245a.pdf

R&D needs in the area of local and wide area power system operation include the following:

- Enhanced definition of requirements for **data management**, calibration, and validation
- Advanced **visualization** tools that incorporate human factors and human-machine interface research to help power system operators effectively interpret the information they receive.
- **Alarm management**/processing tools in control centers that manage information overload, enable real-time root cause analysis, and help operators diagnose problems, and quickly determine needed actions.
- **Fast simulation and monitoring** that provides faster-than-real-time, look-ahead simulations to avoid previously unforeseen disturbances; perform what-if analysis; and integrate market, policy, and risk analysis into system models.
- Development of advanced, low-cost, and accurate **sensors** and optimal deployment of these sensors across the power delivery system.
- A secure, open standards-based, real-time **communications** system that will enable wide-area visualization and robust control
- **Dynamic modeling** of new and evolving power generation sources, as well as improved dynamic load modeling.
- "**Virtual generator**" in which various types of power generation can be integrated with demand response technologies via real-time control to optimize operation.
- **Integration** of many of these advanced technologies into next generation control centers.

Some of this work is being initiated as part of the activities of the IntelliGrid^{SM} Consortium. This international consortium of EPRI, electric utilities, public agencies, and leading equipment manufacturers is accelerating the evolution of today's power delivery infrastructure.

Often Neglected, But Crucial R&D Needs

While avoiding outages receives significant attention, effectively restoring power systems after outages is not currently being addressed as effectively. Yet the duration of the outage directly affects outage costs and the severity of disruption to consumers and the economy. Despite the best efforts to ensure very high reliability, some number of outages is inevitable. Hence, improving methods of restoring the system to lessen their duration and severity is a prudent measure. System restoration enhancement covers a broad range of R&D needs. It involves improving communication systems between operators during restoration, enhancing processing of the multiple alarms that result, improving the quality and timing of data that is received and processed in the control center to aid restoration, enhancing visualization systems to determine the extent of the problem, improving techniques for proper sequencing of restoration steps, and enhancing training methods that cover various outage scenarios.

Power system operation is a challenging profession. Operators must quickly interpret complex information from a variety of sources and satisfy a number of constraints. Most experienced operators have gained the capabilities they need over a period of decades of actual work experience. The impending retirement in the next decade of many of these experienced operators poses a major threat to continued reliability of power system operation. Utilities, as well as ISOs and RTOs, face a critical need for enhanced training programs to equip their novice and less experienced operators with the knowledge and tools they need to effectively operate the system like their predecessors.

Conclusions

In the area of integrated planning, holistic planning involves adopting a “big picture” approach that solves larger problems efficiently at lower cost. This approach would enable system planning for a future of higher carbon dioxide (CO_2) pricing (e.g., the “Double Whammy” or “Biting the Bullet” scenarios) that would change the generation mix and hence impact transmission flow patterns. Similarly, it would accommodate lower natural gas prices (e.g., the “Supply to the Rescue” scenario) that would change the generation mix and impact flow patterns in different ways. Holistic planning would also enable accommodation of a significant increase in high-voltage direct current (HVDC) lines (described in the transmission section), constructed to serve an increase in remote coal-fired power generation (which would be prevalent in a sustained “Digging in our Heels” scenario).

In the area of power system operation, enhanced capability of local and wide area measurement, monitoring, and control is needed for different reasons in different scenarios. In the “Digging in our Heels” scenario, which reflects some conditions today, long neglected transmission investment calls for improved monitoring and control to ensure continued grid operational reliability. In either of the high environmental awareness scenarios, the need for an “efficient” transmission system that minimizes losses, makes best use of existing rights-of-way, and optimally utilizes existing assets is evident. In the “Supply to the Rescue” scenario, the transmission system is likely to be strained to its limits, as high electricity demand spurs high central station power generation growth. In the latter scenario, real-time monitoring and control will be essential to reliable operation of the power system.

In the “Double Whammy” scenario, the transmission system must be able to support efficient wide area operation and control as new power generation at remote locations is transferred to load centers. Because this scenario involves the greatest shift in the resource mix (e.g., addition of nuclear, renewables, storage, electric vehicles, distributed resources, and low emissions fossil units), load patterns will change, transmission congestion will intensify, voltage and dynamic stability problems will occur more often, and dispatch and flow patterns will shift. In this scenario, many of the advances outlined above will be especially important, including dynamic modeling of these new resources, dynamic modeling of the shifting load patterns, improved dynamic stability and voltage stability assessment and control, fast simulation and modeling, and others.

Key R&D Topics

While the technology R&D demands in this subject area are numerous, the five areas described above are particularly noteworthy and span the range of likely challenges (see Figure 6-5):

- Develop cost-effective integrated, inter-regional resource planning tools
- Develop self-healing grid components and control systems (e.g., wide area measurement systems)
- Demonstrate distributed computing tools for real-time grid transient security assessment
- Develop real-time computerized control systems to minimize cascading blackouts
- Implement IntelliGrid tools, including standardized interfaces
- Develop next-generation control centers
- Develop fast simulation and modeling, alarm management, adaptive grid recovery systems and integration with security of electric infrastructure technologies
- Develop advanced tools and methods for rapid, efficient power system restoration

Scenario	"Biting the Bullet"	"Double Whammy"	"Supply to the Rescue"	"Digging in Our Heels"
	High CO_2 prices; Low gas prices	High CO_2 prices; High gas prices	Low gas prices; Low CO_2 prices	High gas prices; Low CO_2 prices
Overview and drivers of technology R&D	Regulation drives need for increase in system "efficiency" and asset utilization	Market forces & regulation drive need for significant increase in system "efficiency"/asset utilization	Expand significantly due to increased reliance on power delivery system	Expand to compensate for past insufficient growth
Technology R&D Gaps: For each scenario, these represent the critical technology R&D needs in the area of grid operations and resource planning.	Enhance traditional transmission expansion planning tools (Critical)	Very critical	Very critical	Very critical
	Develop integrated, inter-regional resource planning tools (Critical)	Very critical	Critical	Critical
	Develop improved tools, fast simulation and modeling, and methods of reliable local and wide-area power system operation (Critical)	Very critical	Very critical	Critical
	Develop more effective system restoration tools (Critical)	Very critical	Very critical	Critical
	Develop more effective operator training tools and techniques (Critical)	Very critical	Critical	Very critical

Legend:
Very critical (solid red arrow)
Critical (dashed orange arrow)
Important (dashed blue arrow)

Arrows indicate that the R&D need applies to *more than one scenario*

Figure 6-5
EPRI Scenario and Technology Development Matrix for Grid Operations and Resource Planning

Distribution Systems

Overview

Compared to the transmission system, the greater complexity, exposure, and extent of the distribution system (e.g., more miles of wire and more poles or conduit) result in greater vulnerability to disruptions. Power disturbances experienced by consumers are most influenced by distribution system characteristics and performance; more than 90 percent of the minutes lost for consumers are attributable to distribution events.

Hence, R&D investments in ways to improve the reliability of the distribution system are paramount for improving consumer satisfaction. One way to do this is to improve the methods and tools available to the workforce that maintains, repairs, and upgrades the extensive distribution systems that criss-cross cities and the country. Advanced construction, troubleshooting, maintenance, and repair techniques and tools are a practical, yet essential area in which R&D is needed. These can include improved methods of dispatching and assigning work to repair crews; improved ways of specifying and testing components to assure their proper application and installation (including standardizing components in some cases), and enhanced maintenance techniques.

Distribution operating costs represent almost 60 percent of total T&D operation expenditures. Hence, designs, tools, practices, methods, and procedures must be in place to achieve the highest possible performance at the lowest cost. Distribution utilities need tools to help them identify optimal designs of distribution systems, assess component population remaining life, develop new inspection and assessment techniques and processes, and educate and train engineering and field staff.

Advanced Distribution Automation

A second way to improve the reliability of the distribution system is to develop and implement a range of new components and systems. Advanced Distribution Automation (ADA) is a concept for a fully controllable and flexible distribution system that will facilitate the exchange of electrical energy and information between participants and system components. With widespread adoption of interconnected distributed resources, the lines between supplier and consumer will blur because many participants will assume both roles and switch effortlessly between these roles, possibly several times a day. The exchange of data and information will facilitate the “supplying” or “using” of electrical energy based on dynamic rather than static prices. Enabling ADA is a principal R&D need in the area of distribution systems.

ADA is distinct from traditional distribution automation (DA). Traditional DA enables automated control of basic distribution circuit switching functions. ADA is concerned with complete automation of all the controllable equipment and functions in the distribution system to improve strategic system operation (see Figure 6-6). The various distribution system components are made interoperable in ADA, and communication and control capabilities are put in place to operate the system. The result is added functionality and improved performance, reliability, and cost, relative to today's system operations. In total, ADA will be a revolutionary change to distribution system infrastructure, as opposed to simple incremental improvements to DA. However, this revolutionary change will occur in an *evolutionary* manner; the tremendous investment in legacy systems will force these changes to occur at a measured pace.

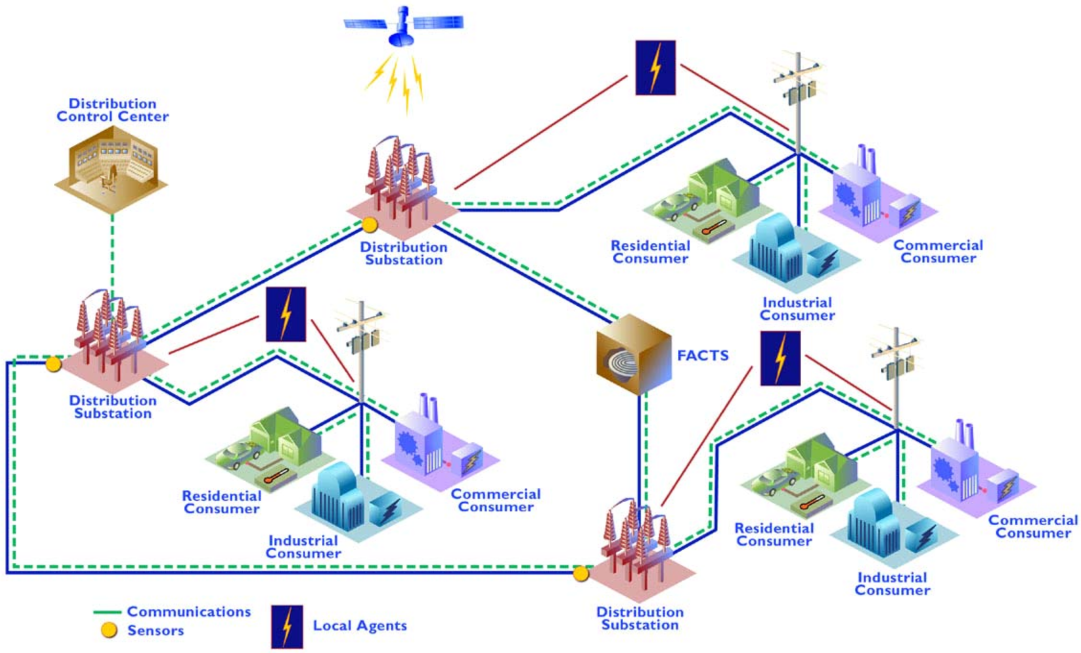

Figure 6-6
This conceptual view of advanced distribution automation shows that sensors, local agents, and an integrated communications system are integral components.

The following five key areas of R&D advances are needed to realize ADA:

- System topologies (i.e., design configurations such as radial and networked)
- Electronic/electrical technology development such as intelligent electronic devices
- Sensor and monitoring systems
- Open, standardized communication architecture
- Control systems

System Topologies

Current distribution system design configurations (radial and networked) have remained virtually unchanged for many years. As the distribution system ages, and demands for reliable and high quality power increase, various advanced technologies (such as those described later in this section) will be adopted. Taking maximum advantage of these technologies requires consideration of various alternative distribution system configurations or topologies. In many cases, a more flexible distribution architecture is needed to realize the benefits of ADA.

Other changes in the industry will also necessitate new configurations. For example, capitalizing on the strategic value of distributed resources (e.g., emergency power, peaking power, volt/VAR support, and sag correction) may require new system configuration options, such as looped feeders, DC ring buses, and intentional islanding (sometimes called "microgrids," see Figure 6-7). R&D needs in this area include development and demonstration of the following:

- Topologies with automated reconfiguration capabilities
- Topologies that allow two-way power flows and local islanding to support integration of distributed resources
- Topologies that support flexible system reconfiguration, microgrids, and consumer system integration.

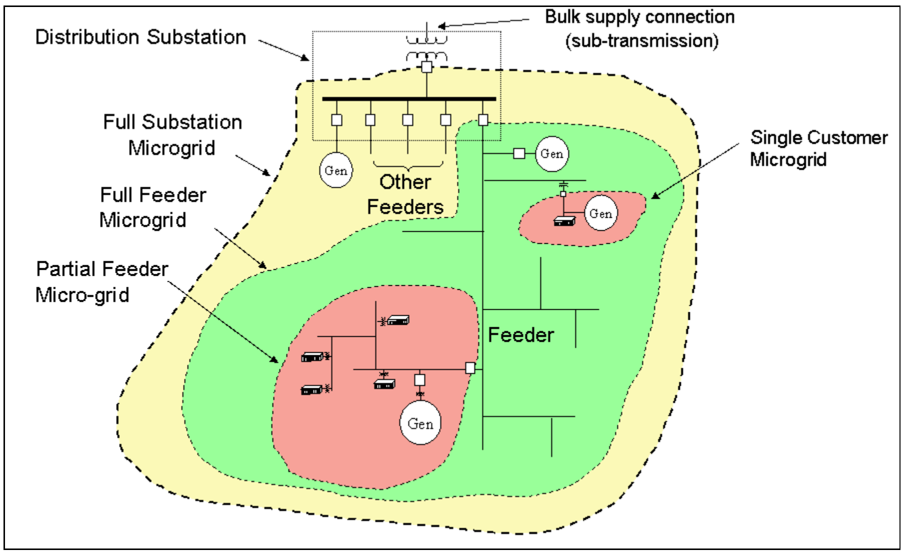

Figure 6-7
An Adaptable Island or "Microgrid" is One Example of a New Distribution Configuration

Electronic/Electrical Technology Development

ADA will accommodate a range of beneficial new intelligent electronic devices (IEDs) that will leverage recent advances in core electrical and electronic technologies (especially power electronics). These IEDs include revolutionary devices like an intelligent universal transformer (IUT), other new power electronics equipment, and distributed generation and energy storage devices.

The IUT is an advanced power electronic system designed to replace conventional distribution transformers. It will provide numerous system operating benefits and added functionality relative to conventional transformers. For example, the IUT will provide alternative customer service options, such as direct current (DC) or 400-Hz alternating current (AC) power for communications applications, while offering power quality enhancement functions like sag correction and harmonic filtering. A highly flexible device, the IUT will be capable of configuration to provide three-phase power from a single-phase line. Its remote communication capability will enable its use as a smart monitoring node in a larger networked ADA monitoring capability. By helping to regulate voltage and power factor, the IUT will help lower electrical losses in the distribution system. It provides adaptable protection functionality to allow islanded and microgrid operation, as well as flexible controls for coordination during normal system operation. Modular in design and reconfigurable in multiple ratings, the IUT will reduce the number of spare transformers needed, compared to conventional transformers. At the same time, the device will contain none of the hazardous liquid dielectrics found in conventional transformers, avoiding the hazards and costs of spills. Last but not least, with the proper R&D, the high voltage direct current (HVDC) bus in the IUT could be configurable to enable energy storage capability.

Significant R&D is needed to make the IUT a commercial reality. R&D is also needed on advanced switched capacitor banks, dynamic voltage regulators, power quality enhancement devices, multi-function distributed resources, and distribution fault anticipators and locators.

To hasten widespread use of electronic controllers on distribution systems, a cost cutting technology R&D breakthrough is needed. Power electronics devices based on materials other than silicon may provide that breakthrough. At this time, the most promising new materials for power electronics are silicon carbide (SiC) and gallium nitride (GaN). Once these devices are in mass production, they promise to reduce the costs of power electronics devices.

Sensor and Monitoring Systems

R&D on real-time distribution system monitoring, diagnostic, and data processing capabilities is needed to allow utilities to optimize real-time system operations, detect and prevent incipient outages, and aid in basic automated operations. To achieve this, system data acquisition via a combination of discrete sensor devices and via monitoring capabilities embedded in system equipment is needed. For example, power electronic components already monitor key electrical parameters, but this information must be accessed. System monitoring functions need to be built into other types of equipment like transformers and switchgear. Waveform analysis capabilities are also needed to provide fault anticipation and other features to aid in strategic operations. Advances in data filtering and processing techniques will be used to create a data management capability, as an integral part of the monitoring system. Also needed are fast simulation and monitoring systems to aid in real-time control.

Benefits of these capabilities will include improved outage prevention and faster recovery, optimal system performance under changing conditions, reduced operating costs, and improved reliability. One component of this work alone, distribution fault anticipation, will detect incipient equipment failures and prevent them from escalating to catastrophic failures. This system will recognize improper equipment behavior in real time and activate control actions to avoid interruptions and outages, and/or to shorten the length of outages when they do occur.

Open, Standardized Communication Architecture

An open, standardized communication architecture, overlaid on the electrical system, is needed to achieve central and local distribution system control. This architecture must enable communication between all smart devices, self identify equipment on the grid, and enable secure operation of the distribution system. In general, the communication architecture will comprise two major elements: computer/communication-based object models and protocols. An object model is a detailed data template for the information exchange needed for monitoring and controlling a device within the architecture of a power distribution system (or other system). The object model makes the device recognizable and controllable (i.e., interoperable) to the power system. This is analogous to hooking up remote devices to a computer. The operating system of the computer interrogates the remote devices, and an interoperable interface is established automatically.

The other principal component of the communications architecture is the communication protocols. Protocols are the rules for transfer of the data within the communication system. For example, the protocols are the rules for transferring information from a distributed resource (as represented in its object model) and transferring the appropriate data to a supervisory control and data acquisition (SCADA) system or other device.

The principal applicable open communication architecture is the utility communication architecture (UCA), which is being standardized via documents such as International Electrotechnical Commission IEC 61850 and others. While standards for substation equipment are complete and much progress has been made in the distributed resource area, much work remains to develop object models for the IUT, smart capacitor banks, load management devices, and various other distribution level power electronic devices. And, as new device types are invented and developed, consensus standards are needed for their object models, to make them interoperable with the open architecture. Adopters of the open architecture approach benefit because they can easily integrate new technologies, if they have been suitably designed and conform to interoperability standards.

Control Systems

To realize the benefits of ADA, more sophisticated protection and control concepts will also be needed – another key R&D topic in this area. As the distribution system becomes more widely monitored via advances in sensor and monitoring technologies, and the system uses more microprocessor-controlled components (e.g., the IUT and new load management devices), use of these components for strategic operating advantage will require a more sophisticated control system. First, the control system must be based on the interoperability of all of its parts. This means migration to the open communication architecture described above. Second, local distribution control via distributed computing will be needed. The local distribution control concept will involve using a central control center at the distribution system level for coordination with controllers at the transmission level. This is necessary for overall power flow supervision and coordination of distributed resource dispatch at the distribution level with central generation at the transmission level, as well as for coordinating volt/VAR management. The central distribution control center would also supervise the distributed control capabilities that are dispersed throughout the distribution system. These include microprocessors embedded in IEDs throughout the distribution system and other local control agents.

Conclusions

R&D for distribution automation is needed independently and to enable distributed resources in a variety of configurations, including adaptive islands and microgrids. This type of R&D has significant value in the “Double Whammy” and “Biting the Bullet” scenarios (see Figure 6-8). In the “Double Whammy” scenario, enhanced demand response and consumer empowerment that is enabled by an energy service portal (see Section 7) will require upgrades to the distribution system. This is also true with widespread proliferation of plug-in hybrid vehicles in this scenario. Similarly, the environmental benefits of technologies such as the IUT (e.g., via avoided hazardous oil spills), and the efficiency of power electronics-based devices and other distribution system upgrades that will result from R&D increases their value in these two scenarios.

The “Supply to the Rescue” scenario, which is a strong scenario for distributed resources (due to low natural gas prices to fuel distributed generation), will also place increased demands on the distribution system. But regardless of the scenario, the same challenges to the distribution system will remain – an aging, asset-intensive infrastructure that must reliably meet growing demands for high quality power.

Hence, ADA remains a high R&D priority across all scenarios. And significant development in the following technology areas is required to achieve the objectives and the vision of ADA:

- Develop an integrated distribution system with storage and distributed generation
- Develop advanced distribution automation tools (e.g., fault location and restoration)
- Develop open, standardized and secure communication architecture
- Develop advanced tools to improve construction, troubleshooting and repair
- Develop solid-state equipment to include the Intelligent Universal Transformer
- Develop flexible electric distribution system topologies (e.g., adaptive islanding, microgrids, and adaptive reconfiguration systems)
- Develop and implement intelligent sensors and monitoring systems
- Develop and demonstrate five-wire distribution system
- Integrate smart metering concepts to enable consumers and utilities to maximize the benefits of night-time recharging of plug-in electric vehicles

Scenario	**"Biting the Bullet"** High CO_2 prices Low gas prices	**"Double Whammy"** High CO_2 prices High gas prices	**"Supply to the Rescue"** Low gas prices Low CO_2 prices	**"Digging in Our Heels"** High gas prices Low CO_2 prices
Overview and drivers of technology R&D	Regulation drives need for increase in system "efficiency" and asset utilization	Market forces & regulation drive need for significant increase in system "efficiency"/asset utilization	Expand significantly due to increased reliance on power delivery system and distributed resources (DR)	Less critical due to reduced penetration of DR, plug-in vehicles, portal, etc., but still important
Technology R&D Gaps: For each scenario, these represent the critical technology R&D needs in the area of distribution systems.	Develop range of methods and tools to improve construction, troubleshooting, maintenance, and repair of distribution systems and components			
	Develop flexible electric distribution system topologies			
Legend: Very critical Critical Important Arrows indicate that the R&D need applies to *more than one scenario*	Develop key electrical and power-electronic components, including intelligent universal transformer			
	Develop and implement intelligent sensors and monitoring systems			
	Use open, standardized communication architecture and systems			
	Develop and demonstrate real-time distribution system monitoring, diagnostic, and data processing capabilities			

Figure 6-8
EPRI Scenario and Technology Development Matrix for Distribution Systems

Power Quality

The Impact of Digital Loads

The nature of electricity demand is undergoing a profound shift in North America and industrialized nations around the globe. Over 20 years ago when the personal computer was introduced, few foresaw the widespread proliferation of microprocessor-based electronic devices. Today, for every microprocessor inside a computer, there are over 30 more in stand-alone applications, resulting in the digitization of society (see Table 6-1). In applications ranging from industrial sensors to home appliances, microprocessors now number more than 12 billion in the United States alone.

Table 6-1
The Broad Spectrum of Digital Systems, Processes, and Enterprises

Digital Devices	Digital Applications	Digitally-Enabled Enterprises
Microprocessors • Central processing units • Programmable logic arrays • VLSI chips Embedded Controls • Programmable controls Interface • Sensors • Transducers • Liquid crystal display • Modem	Residential • Appliances • Security • Home office Commercial • Office equipment • Networking • Data processing Industrial • Process control • Automation • Quality	Security • Image analysis • Digital video • Motion detection Banking/finance • ATMs and electronic transfers E-commerce • Online shopping • Electronic inventory • Paperless transactions Data management • Web hosting • Outsource storage and retrieval

These digital devices are highly sensitive to even the slightest disruption in power (an outage of less than a fraction of a single electrical alternating current cycle can disrupt performance). Digital devices are also sensitive to variations in power quality (PQ) due to transients, harmonics, and voltage surges and sags. “Digital quality power,” with sufficient reliability and quality to serve these growing digital loads, now represents about 10 percent of total electrical load in the United States, and this percentage is expected to reach 30 percent by 2020 if expected trends continue.

Current State of the Power Delivery System

However, the current electricity infrastructure in the United States, designed decades ago to serve analog (continuously varying) electric loads, is unable to consistently provide the level of digital quality power required by digital manufacturing assembly lines, digital-based information systems, and even home appliances in the not to distant future.

Various investigations have revealed that the single most potent cause of end user PQ problems is voltage sags or swells. The second most vigorous contributor is harmonics – unwanted frequencies (i.e., not 60 cycles per second), voltage or current waveforms. The next heavy hitter is inadvertent electrical grounding/faults and other wiring issues. Sags in voltage supplied to digital systems are a growing concern – one of the most common causes of PQ problems (see Figure 6-9). Various sources of utility PQ data also provide a picture of the quality of utility supplies (see Table 6-2).

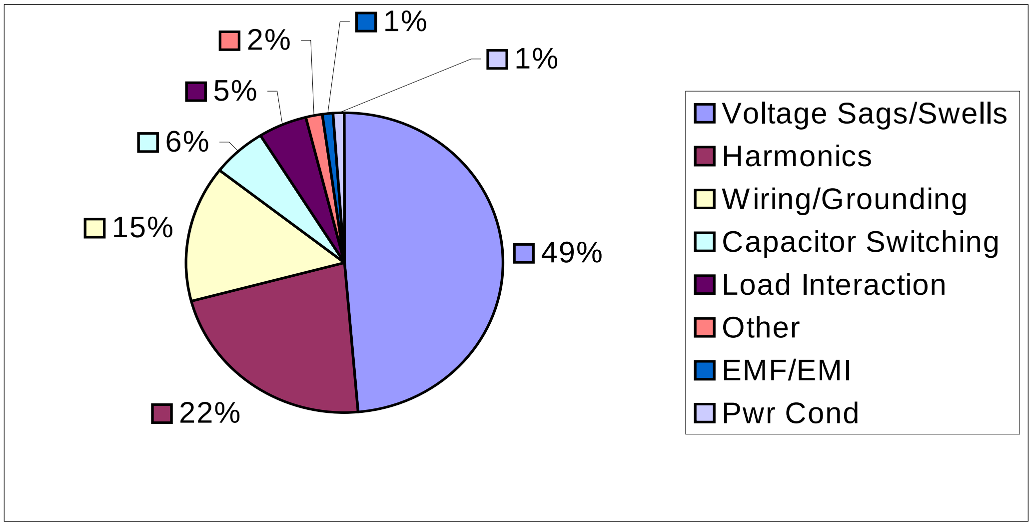

Figure 6-9
Breakdown of the PQ Phenomena Found in Over 500 EPRI-sponsored Investigations

Table 6-2
Default Utility Supply Characteristics for Reliability and Quality Analysis

	Utility Supply Quality Levels (typical number of events per year)			
	1 Moderate Voltage Sags	2 Severe Voltage Sags	3 Momentary Interruptions	4 Long-Duration Interruptions
Rural distribution supply	28	13	7	3
Suburban distribution supply	19	8	3	1.3
Urban distribution supply	12	4	0.7	0.2
Urban network supply	12	4	0.02	0.02
Transmission supply	5	1.5	0.9	0.7

The Path to the Future

Given the demands of end users for high quality power and the current inability of the power delivery system to provide quality power for selected digital loads, one perceived solution is to improve the quality of power that utilities deliver, by providing consumers “a clean sine wave.” Original equipment manufacturers could then assume this level of PQ exists and they can offer appropriate commercial equipment. However, the cost of providing a clean sine wave at all times to all consumers would be enormous and virtually impractical. The required electric infrastructure upgrades would take a long time to implement, and utilities would need to pass the high implementation costs on to all electric consumers.

An alternate approach would be to significantly increase the resilience of all end-use equipment (via retrofit or new purchase of improved equipment) to PQ fluctuations. However, this is also impractical, would significantly increase the cost of this equipment, and would also take a long time to accomplish.

A third option that appears to be a promising compromise, is to promote advances in two parallel areas: 1) utility providers would offer a menu of “grades” of power (and improve the power delivery system in order to provide such power), and 2) equipment manufacturers would design end-use devices to tolerances that match these grades of power. Today, consumers purchase gasoline in three different “grades” corresponding to standardized octane levels of 87, 89, and 91. Similarly, consumers would purchase power according to various grades. These grades would be defined so that the best grade meets the needs of highly sensitive loads, the lowest grade would meet the needs of ordinary loads without special requirements, and intermediate grades would meet the needs between these two extremes. For example, an industrial consumer might purchase the highest grade of power to operate its assembly line, because even a momentary power interruption would require hours to reset, result in high costs in lost productivity, and damage products. This same consumer might purchase low grade power for its heating, ventilating, and air conditioning (HVAC) and lighting systems in its office space, because momentary or short outages could be tolerated for these types of electric loads.

Such an arrangement would require establishment of clearly defined, broadly accepted, standardized grades of power that manufacturers, utilities, and consumers would use. Once these grades of power are standardized and offered, a network of sensors and monitoring equipment would be required to ensure that the power is delivered according to the standards, and that the equipment is manufactured to these tolerances. Sensors would need to be embedded in end-use equipment and distributed across the power delivery network. Also needed is a means of reliably communicating information between end use electric loads and utilities, and across the power delivery system.

At the end-use level, compatibility of the end-use equipment and the power delivery system goes both ways; the device must operate effectively if provided the proper grade of power, and it must not itself degrade the quality of power in the local power delivery system via its operation. To substantially increase the tolerance of products to various power quality phenomena, embedded solutions would proliferate. Such embedded solutions are not in common use today, and technical barriers block their emergence, so R&D is clearly needed in this area.

In parallel, another "grade" of power could be offered – DC power; for many uses of electricity, DC systems are more efficient than AC systems. For example, an office building with a significant computer equipment load could employ a DC bus for its digital server based information technology equipment, and use AC power for its remaining loads. Purchasing DC power would be analogous to purchasing diesel fuel instead of one of the octanes of unleaded fuels. DC power also would serve a range of practical applications in industrial plants, as well as in DC microgrids (refer to the distribution section of this report for more information on microgrids).

Some consumers and most utilities would need economic tools to determine the best combination of options to meet their needs. Consumers would need to examine the costs of the various grades of power at different times of day, compare these costs with their outage costs, and determine which type of power to purchase for which applications at specific times of day. This analysis is complicated by the fact that PQ is not the only criterion that consumers may want to use to characterize its power needs. For example, consumers need to be able to evaluate four distinct electric power characteristics for the electric power they purchase: quality, reliability, security, and availability. This requires advances in the standardization of metrics used for each of these power characteristics. The goal is for consumers to be able to determine the optimal combination of these four characteristics for their various needs.

Utilities would need economic tools to determine how best to set pricing for the various grades of power at various times of day and parts of their service territory, and determine the optimal combination of equipment and measures to employ to ensure that they meet their obligation to consumers. Of course, effective communication and training on these new "products" would be needed for all stakeholders.

Success Statements for Power Quality: A First Step

EPRI has identified 16 "success statements" that articulate the specific needs and goals for ongoing PQ research in the next ten years. These statements, restated below as R&D needs, were carefully identified and crafted in close cooperation with utility and industry PQ professionals. Collectively, the 16 success statements provide a basis for identifying key needs and opportunities in PQ; serve as a means of keeping research focused on specific, achievable, and economically viable solutions; and enable charting and quantifying of annual progress. These R&D needs are grouped into the following four areas:

Improving PQ via power delivery system design, maintenance, and planning

- Dynamically benchmark the ongoing performance of the power deliver system.
- Dynamically update electric supply PQ models based on real-time data.
- Identify economic opportunities for improved PQ and develop PQ goals (via metrics such as value of load not served) for benefiting from improved PQ
- Develop a robust 10-year forecast to help project the PQ composition of future electric loads.

Achieving cost-effective PQ compatibility between the power delivery system and loads

- Develop a universal equipment immunity standard for electronic equipment, perhaps through the Institute of Electrical and Electronics Engineers (IEEE), and develop a testing standard and certification method.
- Develop a comprehensive equipment design guide that is widely adopted within the equipment design and manufacturing industry.
- Determine what consumer segments are suffering PQ problems.
- Develop a compatibility standard for voltage immunity.
- Develop a comparable level of understanding about compatibility and PQ issues for AC and DC.

Integrating PQ monitoring

- Design and deploy a PQ monitoring system that is fully compatible with key electrical system equipment and PQ monitoring and data gathering systems.
- Integrate sensors/monitors in all important system devices.
- Deploy ubiquitous and sufficiently high-speed PQ monitoring systems that are integrated with sophisticated device/system models to allow prevention of all preventable equipment failures.
- Develop tools (hardware and software) to strive to anticipate all preventable electric faults.
- Develop and deploy PQ monitoring systems that identify and flag all preventable/intermittent phenomena (e.g., develop a means of determining occurrence of a lightning strike), and determine the location of electrical problems with great accuracy.
- Develop and deploy PQ systems that detect and locate faults on a map, preferably from PQ or other readily-available data sets.

Ensuring effective communication and training

- Automate the means to deliver power quality information and training material to maximize economic value.

PQ standards are not sufficiently advanced today. Without such standards, these 16 topics cannot be quickly or adequately addressed.

Conclusions

From a scenario point of view, PQ is a growing concern in the “Digging in our Heels” scenario and especially in the “Supply to the Rescue” scenario. In the latter scenario, load growth will occur at a rate higher than improvements in the T&D system, which will likely result in voltage sags on the T&D system. This challenge alone points to the need for PQ solutions in this scenario (see Figure 6-10).

PQ challenges tend to rise whenever any new type of device is interconnected to the power delivery system. For example, the widespread proliferation of distributed generating units would raise a range of complexities at a large number of points across the power delivery system (e.g., the safety of repair crews during outages would be compromised due to distributed low voltage generators energizing lines while repair crews are trying to repair them). Similarly, renewable technologies can exacerbate PQ problems. Wind power generation and photovoltaic generation initially generate variable frequency AC power and DC power, respectively, which must be transferred, rectified, and/or converted to 60-Hz AC power. This conversion can introduce AC harmonics into the power delivery system. Charging systems for plug-in hybrid electric vehicles are another source of harmonics. Hence, PQ issues will be particularly acute in scenarios in which distributed resources, renewables, and electric transportation proliferate (e.g., the "Double Whammy" scenario and to a lesser extent, the "Biting the Bullet" scenario).

Key R&D Topics

Following is a list of the key R&D topics for the area of power quality:

- Improve power quality by advanced designs, equipment, controllers and maintenance tools
- Perform power quality benchmarking analyses to include standards development
- Develop power quality tools to integrate distributed generation and storage
- Develop power quality compatibility tools on AC and DC equipment
- Develop economic value proposition for improving power quality

Scenario	"Biting the Bullet" (High CO_2 prices; Low gas prices)	"Double Whammy" (High CO_2 prices; High gas prices)	"Supply to the Rescue" (Low gas prices; Low CO_2 prices)	"Digging in Our Heels" (High gas prices; Low CO_2 prices)
Overview and drivers of technology R&D	Renewables, distributed resources, and plug-in vehicles exacerbate PQ problems, motivating action	Renewables, distributed resources, and plug-in vehicles exacerbate PQ problems, motivating action	Strain on the power delivery system (and resulting voltage sags) motivates action	Existing demands for higher power quality motivate action
Technology R&D Gaps: For each scenario, these represent the critical technology R&D needs in the area of power quality.	Focus on impacts of, and integrate, renewables, distributed resources, and plug-in vehicles	Focus on impacts of, and integrate, renewables, distributed resources, and plug-in vehicles	Focus on voltage sags due to strain on power delivery system	
Legend: Very critical; Critical; Important. Arrows indicate that the R&D need applies to *more than one scenario*	Improve PQ via power delivery system design, maintenance, and planning (benchmarking, modeling, forecasting, economic analysis)			
	Achieve cost-effective PQ compatibility between the power delivery system and loads (standards, equipment design guides, AC & DC)			
	Enhance PQ sensors and monitoring, on power delivery system and in end-use equipment, to ensure compatibility; anticipate and locate faults and failures			
	Develop economic value proposition for improving power quality			

Figure 6-10
EPRI Scenario and Technology Development Matrix for Power Quality

Physical and Cyber Security

Overview

Because electricity drives so many of the nation's critical infrastructures, the power system presents an attractive target to terrorists as well as disgruntled former or current employees. A coordinated attack against major power plants or substations could result in a cascading blackout, causing a major national economic disruption. As a result, industry experts agree that comprehensive security improvements are necessary to prevent attacks against the system, mitigate the effects of successful attacks, enable rapid recovery, and communicate accurate, timely, and actionable information about security threats to all organizations within the electrical power system. (For the purpose of this section, "security" refers to security against physical and/or cyber attack or intrusion, as opposed to a reliable, secure power delivery system.)

In the current climate, there are two areas of growing concerns: threat of physical attack or sabotage, and the threat of electronic "cyber" attack. While physical security has been an industry concern to some extent for decades, the threat of cyber attack is comparatively new. However, with the increased reliance on software for grid operations and control centers, the growing use of Internet technologies for both front- and back-office operations, and the increase of wireless sensors in the grid, effectively addressing this area of vulnerability is critical.

Potential security threats are additionally compounded by the growing adoption of open system software within supervisory control and data acquisition (SCADA) systems, the use of the Internet as a communications channel, and the integration of common transmission control protocol/internet protocol (TCP/IP)-based corporation communication networks. And, the need for utilities to share real-time SCADA data with their own business systems as well as with other organizations increases the potential for security vulnerabilities (see Figure 6-11). While the growing interdependence of corporate IT systems and control systems is a boon for business operations and reliability, security flaws in any part of the business infrastructure could potentially enable hackers to access control systems.

While these two areas of concern – physical security and cyber security – are logically separate, industry experts predict that the electrical system is especially vulnerable to a hybrid threat (a physical attack on facilities and equipment, coupled with a cyber attack). A successful attack could result in lengthy, large-scale outages and significant financial losses for the industry as well as the national economy as a whole.

The overall R&D goal in this area is to harden the power system against physical and cyber attack and enable the system to recover quickly in the event that an attack occurs, while still enabling operators to reap the benefits of new network-based technologies. Working with utilities that already face physical attacks, such as those in Israel and other countries, is beneficial. The ability of these organizations to maintain electric power despite threats and successful attacks to their electric power system infrastructure is noteworthy. Obtaining lessons learned and a description of the types of technologies implemented by these organizations that address physical and cyber security issues is valuable.

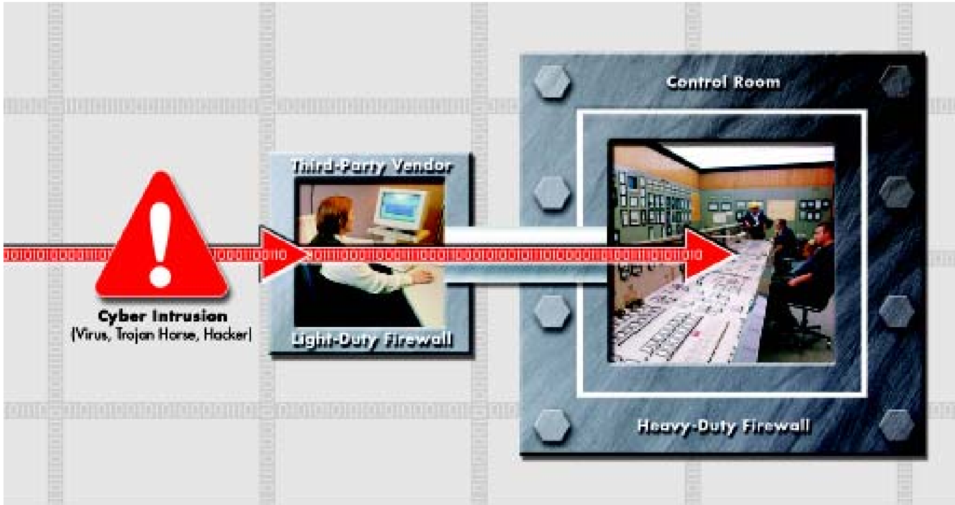

Figure 6-11
While utilities go to great lengths to protect their critical facilities from cyber intrusion, their connections with third-party vendors can be an unrecognized weak spot.

Hackers stopped by strong cyber firewall systems protecting the control room, for example, may be able to gain access through weaker, standard security measures protecting vendors that provide procurement or billing services. Once "in the back door," the intruder may be able to move to a utility's or operator's grid operations and control systems and cause grid system outages. Photo courtesy: *EPRI Journal.*

Physical Security

While the chance of an attack on the power system is statistically low on any given day, a successful, coordinated attack could results in blackouts costing millions or billions of dollars. Specific areas of vulnerability that can be addressed through coordinated R&D are addressed in the following subsections.

Rapidly Deployable High-Voltage Transformers and Other Equipment

The custom-designed large power transformers at transmission substations are key components needed for reliable operation of the power system. Currently, the design of each transformer is unique, with the optimization of power delivery capacity, impedance, dielectric withstand strength, voltage transformation ratio, and losses for the particular grid interconnection where it is located. As a result, quick replacement of high-voltage transformers in the event of unplanned outages is extremely difficult – there are few, if any, viable "plug and play" transformer replacement options. Currently, spare high-voltage transformers are often built at the same time and stored next to the units they are designed to replace; while this speeds recovery time in case of mechanical failure, it also increases the possibility that the only available spare for the item will be damaged or destroyed during an intentional attack.

Current projects to improve the feasibility of replacing transformers include EPRI's Infrastructure Security Initiative (ISI), which determined the feasibility of building rapidly deployable transformers to be used in case of multiple transformer outages. These transformers were designed for flexible application across a range of voltage configurations, minimal deployment time, reliable service life, and rapid manufacturing.

The project concluded that recovery transformers that meet these requirements are feasible and can be deployed in a wide variety of different utility grid conditions. If these units are built, stored in strategic locations, and effectively maintained, properly trained personnel should be able to restore power service in areas affected by wide-scale transformer outages in only a few days, after the equipment is shipped to the site attacked. EPRI efforts in this area resulted in a detailed specification for recovery transformers, electrical designs to cover the specific needs of the largest number of transformers in service in the United States, and detailed mechanical components and field installation processes necessary to support expedited deployment and installation.

To realize the potential of the rapidly deployable recovery transformer, additional R&D is needed in the following areas:

- Design, manufacture, and test prototypes of the recovery transformer
- Design and perform field tests to rapidly deploy prototype recovery transformers in host utility substation environments to demonstrate the concept in an actual operating environment, and identify potential barriers to full project implementation
- Identify the location of infrastructure support for recovery transformers, including storage locations, transportation, and processing systems
- Modify the concept as necessary to build a sufficient quantity of recovery transformers at various voltage and power ratings to meet the recovery needs of the North American power system; and train personnel on their deployment (based on the results of the preceding R&D areas)

Replaceable Control Systems and Operations Equipment

Control systems at substations are also physically vulnerable to attack. To enable the most rapid recovery after an event, R&D is needed to aid utilities in the design and deployment of a rapid recovery plan that includes:

- Rapid procurement and deployment of replacement control system hardware
- Swift installation and configuration of system-specific software, data, control algorithms, protection relay systems, switching information, and other items needed
- Adequate training (e.g., field test drills) for personnel to respond swiftly and surely in the event of an attack

Physical Plant Security

The physical security for generation facilities and supporting infrastructure also requires improvement. While nuclear power plants have designs to protect containment vessels sheltering radioactive material from attack, cooling towers are still vulnerable to destruction by physical attacks. In the event of an air attack, a radioactive incident will very likely be avoided, but generation capabilities could be halted. Similarly, an attack at a hydropower plant could result in downstream flooding.

With widespread access to satellite mapping information through public services such as Google Earth, physical facility information that was previously difficult to obtain can now be located with ease. As a result, utilities will benefit from research into methods of physically securing their assets, such as improved air and perimeter monitoring systems with advanced video pattern recognition systems to identify anomalies and alert personnel and law enforcement immediately. In addition, personnel must be trained on implementing safety procedures when an alert occurs.

Cyber Security

Because the industry is increasingly dependent on the Internet and computerized monitoring and grid control systems, a serious attack on the electrical power system need not be directly physical. Internet-based or “cyber” attacks can enable perpetrators to disrupt a utility’s computer network or power grid control system while remaining anonymous and remote. And, with electric power networks so tightly interconnected, a significant single cyber security breach can affect the system as a whole. Recent industry trends that impact cyber security include the following:

- The use of common operating systems such as Microsoft™ Windows and UNIX in power control systems. Though these widely used operating systems reduce administrative burden and improve system interconnectivity, their public nature makes them more vulnerable to security flaws and attack.
- The increased used of TCP/IP communications. While improving commonality and economies of scale within a corporate network, TCP/IP use opens operational networks to the same vulnerabilities as corporate networks, particularly through the Internet.
- Demands for real-time data. In many utilities, business demand for real-time operating data has resulted in connection of corporate systems to operating systems. In addition, deregulation has created the need to share real-time data among various entities within the power system instead of within a single vertically integrated organization. Any system that shares data with another exposes vulnerabilities that must be addressed.

Overall, cyber security threats can target the four following critical areas:

- SCADA system hardware and software
- Energy management systems (EMS) hardware and software
- Distributed control systems (DCS) used to operate substations and power plants

- Communications media and systems including connectivity through Internet, private lines, remote telemetry/terminal units (RTUs), as well as internal, wireless, telephone, radio, and microwave networks
- Interfaces between utility operations and back office systems with a focus on hardening interfaces between operations and back office corporate networks

Existing industry efforts to address information security issues include PowerSec, an alliance of EPRI, the Edison Electric Institute, North American Electric Reliability Council (NERC), and the Idaho National Laboratory. PowerSec's primary purpose over the long term is to assess the vulnerability to cyber threats throughout the industry; develop and deploy tools and procedures to improve cyber security of the power grid and power plant equipment; and train and certify utility personnel to effectively use these tools and procedures (see Figure 6-12).

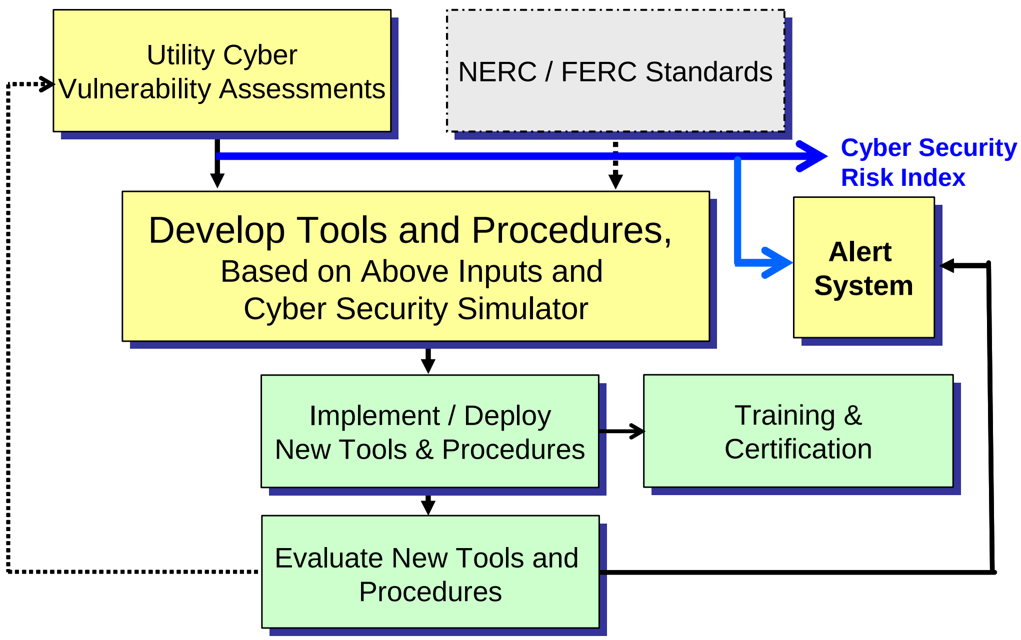

Figure 6-12
This PowerSec approach shows key cyber R&D needs, including vulnerability assessment, new tools and procedures, training, and an alert system

To address the growing cyber security concerns, NERC adopted eight new cyber security standards that address asset identification; security management controls, personnel and training; perimeter security; systems security; incident reporting and response planning; and recovery plans. Utilities will benefit from R&D that identifies the most effective ways to comply with these standards. Critical areas of research are discussed in the following subsections.

Ongoing Comprehensive Vulnerability Assessments

To address cyber security in an organized manner, comprehensive vulnerability assessments should be conducted throughout the industry for individual power producers, power system operators, and interconnection points between systems. Because of the changing nature of the threats, ongoing assessments and associated security revisions are a necessary element of cyber security planning. Research is needed to develop and disseminate an effective model for assessing the cyber vulnerabilities of the entire operating environment, including business systems, control systems, and their interconnection points.

New Security Tools and Procedures

The results of the vulnerability assessments identify the areas of greatest need for the development of new cyber security tools and procedures. These are likely to include the following:

- System-wide monitoring, intrusion detection, and operator alerts
- Effective access control through authentication, authorization, and non-repudiation
- Protecting data from access or damage
- Mitigating damages caused by successful attacks, and ensuring a rapid recovery

Wide-Scale Alert System

The tools and procedures described above should enable operators to respond to threats in their own environment. But in addition, the power system as a whole needs a real-time wide-scale alert system that informs other power producers and power system operators that a portion of the power system is under attack. This system should also characterize the nature of the attack to enable stakeholders to improve their own defenses against a similar assault.

Security Issues Common to Both Areas

While ensuring physical and cyber security each pose unique requirements, a range of issues common to both areas must also be addressed in order to ensure reliable power delivery.

Interdependency Analysis

The ability of the power system to function is dependent on a host of other industries, including fuel pipelines, water supply, telecommunications, and others. An attack on the national utility infrastructure that does not directly damage the power system can still disrupt reliable power generation. For example, an attack on fuel pipelines or the intercommunication with supporting systems can interrupt power supply as effectively as an attack on the electrical system itself.

To address threats to the power system caused by attacks on supporting infrastructures, R&D is required to identify vulnerabilities, improve communications with supporting providers, and develop and implement comprehensive contingency and backup plans to ensure continued power delivery in case of an attack on a supporting system.

Training and "Red Team" Development

A common theme through all areas is the need for comprehensive and ongoing training. To ensure that personnel can respond rapidly and automatically in the case of attack, training must extend beyond workshops to include "war games" – exercises in which employees respond to simulated attacks. To enable this kind of training, a group similar to the Federal Aviation Administration's "Red Team" should be developed, with the dedicated purpose of staging realistic mock assaults against utilities so that the effectiveness of emergency response throughout the organization can be analyzed and improved.

R&D is required to develop and disseminate best practices for organization-wide security training, to design methods for effective Red Team tactics, and to evaluate and improve utility response to simulated attacks.

Ongoing Security Evaluation and Improvement

As technological vulnerabilities and physical plant security issues increase in complexity, ongoing physical and cyber vulnerability assessments are required to identify new gaps that result in improved procedures and training. In addition, all elements of the security plan must be continually tested and revised to ensure comprehensive protection throughout the electrical power system.

Conclusions

According to a report published by the Israel Electric Corporation, a utility that regularly defends its grid against terrorist attacks, the most critical elements of a successful security program are the following:

- **People:** Security depends on hiring qualified people, conducting extensive security training, ensuring awareness of security issues, including personnel in the development of security solutions, and conducting frequent security exercises that cross department boundaries.
- **Procedures:** A comprehensive body of procedures should be developed for each department and each person responsible for decisions and actions in the departments. Staff must be frequently trained to address a variety of emergency situations, and the procedures must be regularly audited and revised based on lessons learned within the company and throughout the industry.
- **Technology and equipment:** Throughout the industry, operators should harden control centers, backup dispatch control centers, and communication systems; develop and deploy an independent secure emergency communication system; and stockpile spare parts in rapidly deployable, secure, and safe locations.

Comprehensive and ongoing R&D in the above areas – as well as the dissemination and implementation of the results – are needed to secure the nation's critical power infrastructure against the real possibility of organized physical and cyber attack.

The power delivery and power generation systems in North America are arguably at their most vulnerable when they are pushed to their limits. When little reserve margin exists in either power generation or transmission capabilities, a physical and/or cyber terrorist attack would pose the greatest potential consequences. This is analogous to the vulnerability of a subway train to terrorist attack at rush hour. In the “Supply to the Rescue” scenario, existing centralized power generation is relied upon to meet electricity demand, which will be growing at a significant rate in this scenario. Similarly, the power delivery system is likely to be strained to the limits of its operation a larger percentage of the time in this scenario; with supply solutions paramount, the wide area power system will need to deliver this power reliably. Hence, security needs are particularly acute in this scenario.

The “Digging in our Heels” scenario reflects some of today’s conditions. Long-neglected investment in the transmission infrastructure has led to operation close to thermal and stability in limits in many parts of the country during peak periods. Hence, security R&D is especially needed in this scenario.

The “Biting the Bullet” and “Double Whammy” scenarios rely less (although not significantly less) on central power generation and wide area power delivery systems. The diversification afforded by distributed resources, new power generation facilities of various types, growth in demand response, and other measures decentralizes power generation and delivery. Yet a coordinated attack on the electric power infrastructure could still wreak havoc under the conditions of these scenarios. Figure 6-13 shows that security R&D and solutions are slightly less pressing in these scenarios, but remain important.

Key R&D Topics

Following is a list of the key R&D topics for the area of physical/cyber security:

- Conduct vulnerability-interdependency analyses of electric, communication and fuel sectors
- Develop software tools to protect cyber assets from internal or external attacks
- Demonstrate Recovery Transformer to rapidly and successfully respond to major outages
- Develop and perform verification of inter-regional emergency test protocols
- Develop hardware tools to protect physical assets from internal or external attacks
- Ensure cyber protection of Supervisory Control and Data Acquisition (SCADA), Energy Management System (EMS), Distributed Control Systems (DCS), and communications systems and interfaces
- Conduct comprehensive grid equipment cyber vulnerability assessments; and develop wide-scale cyber threat monitoring and alert system
- Provide tools, and conduct and improve cyber and physical security training and “red teaming” exercises
- Develop and deploy grid security monitoring, disturbance detection, and disturbance location and mitigation system
- Establish industry-wide communication and alert system

Scenario	**"Biting the Bullet"** High CO_2 prices Low gas prices	**"Double Whammy"** High CO_2 prices High gas prices	**"Supply to the Rescue"** Low gas prices Low CO_2 prices	**"Digging in Our Heels"** High gas prices Low CO_2 prices
Overview and drivers of technology R&D	Decentralized and diversified power generation options, and lessened reliance on wide area power delivery systems reduces risks, but potential consequences remain high	Decentralized and diversified power generation options, and lessened reliance on wide area power delivery systems reduces risks, but potential consequences remain high	Heavy reliance on centralized power generation and a strained power delivery system increase the potential consequences of an attack	Long neglected investment in the wide area power delivery infrastructure increases the potential consequences of an attack
Technology R&D Gaps: For each scenario, these represent the critical technology R&D needs in the area of physical and cyber security.	Demonstrate rapidly deployable high-voltage transformers, replaceable control systems, and improved physical plant security			
	Ensure protection of SCADA, EMS, and DCS systems; and communications systems and interfaces			
Legend: Very critical Critical Important Arrows indicate that the R&D need applies to *more than one scenario*	Conduct ongoing comprehensive vulnerability assessments; develop new cyber security tools & procedures; and wide-scale alert system			
	Conduct interdependency analysis and implement protective measures (other infrastructures)			
	Conduct training and "red teaming"			

Figure 6-13
EPRI Scenario and Technology Development Matrix for Physical and Cyber Security

7

TECHNOLOGY R&D NEEDS: END USES OF ELECTRICITY

This section covers technology R&D needs related to end uses of electricity. It addresses the following topics:

- The energy service portal
- End-use energy efficiency, including improved industrial processes (e.g., electrotechnologies), commercial and residential improvements (e.g., lighting; heating, ventilating, and air conditioning; office technologies; and household appliances)
- Electricity-based transportation

Energy Service Portal

Overview

The energy service portal empowers consumers by enabling them to make intelligent decisions about energy consumption. Beyond the benefits to consumers in reduced energy costs, the energy service portal can also help reduce the need for new power plants, transmission lines, and distribution lines by facilitating demand response and other positive measures. This, in turn, minimizes transmission congestion, avoids outages, improves reliability, and reduces the environmental impact of power generation emissions. Clearly, a successfully implemented energy service portal offers benefits to consumers, utilities, and society.

The energy service portal is a combination of hardware and software that supports communication between consumers and between consumers and the utility, which enables the consumer to directly manage power-consuming devices. The successful implementation of the energy service portal could fundamentally transform the relationship between power suppliers and consumers. The portal enables a broad array of services, such as demand response, real-time pricing, outage detection, and others that empower consumers and reduce utility costs. In addition, the two-way flow of communication data could enable a new generation of high-value power, information, and entertainment services. Potential uses of an energy service portal include the following:

- **Improved energy management for the consumer.** Because consumers can receive information about demand to directly manage the devices that use electricity through a single interface, they can respond to price signals and modify their energy consumption accordingly. These capabilities are particularly important in scenarios that include high electricity prices (e.g., the "Double Whammy" scenario).
- **Value-added home management services.** An energy service portal can easily incorporate various home security and management functions such as immediate notification of unauthorized entry; automatic sensing and diagnosis of mechanical problems with any of the "smart" equipment connected to the portal; and emergency alert capabilities for consumers with health issues. For example, a portal-connected smart refrigerator could signal the age, freshness, and replenishment schedule for perishable foods, as well as provide advanced alerts regarding maintenance or repair. Thus, the number of services that an energy service portal can support is very high.
- **Information and entertainment services.** With a comprehensive low-cost energy service portal in place, utilities would be uniquely well-positioned to provide consumers a range of content-related services through a reliable digital infrastructure, such as internet access, real-time pricing, and video and audio entertainment.

Energy service portals offer benefits to utilities as well. Consumer relations are improved by empowering consumers to make cost-effective choices about energy consumption. In addition, a portal can support other consumer-friendly functions such as automatic billing, notification of unusual energy consumption, feedback to consumers on their energy use trends over time, and intruder/theft monitoring and detection. By enabling consumer demand response through the portal, utilities can avoid the need to build additional generation, transmission, and distribution capabilities that might be intermittently used during periods of peak demand. This capability is particularly useful in scenarios that rely heavily on the power delivery system, such as the "Supply to the Rescue" scenario. Table 7-1 contains a selection of potential portal applications that are considered most promising (based on EPRI's IntelliGrid Consortium).

While these kinds of traditional power-related services will improve the status quo, forward-looking energy companies can seek to improve profitability by leveraging a ubiquitous, easy-to-use portal interface, and connectivity to most electronic devices in the home, to offer a range of unbundled high-value information and entertainment services.

Many utilities and vendors have attempted to implement energy service portal systems over the past two decades, with each providing a wealth of lessons-learned. These experiences provide an important foundation for understanding the areas that require additional efforts to foster the feasibility and market acceptance of widespread portal deployment. R&D opportunities to further the development of all aspects of the energy service portal and the services it enables are described in this section.

Portal Development and Deployment

An energy service portal can be thought of as a "virtual device" – a set of applications and interfaces that may be located within a meter, a thermostat, a computer, a television set-top box, a stand-alone device, or any other device or appliance at a consumer site. All the devices in the portal can be monitored and managed through an easy-to-access user interface, available to the consumer at any time through the Internet or even via mobile phones. Figure 7-1 shows the elements of a possible portal.

Table 7-1
Selection of Most Promising Energy Service Portal Applications

Function	Application	Overall Rank (1 to 5; 5 is highest)
Utility-based	Automatic meter reading (AMR)	4
Utility-based	Avoided cost of new generation, transmission, and distribution	5
Utility-based	Value of consumer loyalty, goodwill, and reputation of utility	4
Utility-based	Theft detection	4
Utility-based	AMR for multiple meters (electric, gas, and water)	3
Utility-based	Advanced AMR (e.g. profiling, interval counters, demand usage, etc.)	3
Utility-based	Other synergistic network benefits	3
Energy pricing/demand control services	Demand response (with elasticity = -0.1 to -0.3)	5
Energy pricing/demand control services	Real-time/spot pricing (RTP), minutes to days ahead	5
Energy pricing/demand control services	Load shedding	4
Energy pricing/demand control services	Air conditioning load cycling capabilities	4
Commercial & industrial consumer functions	Usage optimization (e.g. energy management system equipment control/management)	4
High-use residential consumer functions (energy-related)	Energy usage optimization (e.g. HVAC, pool pumps, and electric water heaters)	4
High-use residential consumer functions (non-energy related)	Homeowner use of portal as a common interface for other applications	4
High-use residential consumer functions (non-energy related)	Non-energy services (variety of other value-added services)	4
Regulatory/government-driven functions	Regulatory issues (e.g. mandates)`	5
Regulatory/government-driven functions	Homeland security and grid reliability value	4
Regulatory/government-driven functions	Potential reduction in outages and lost societal value	4

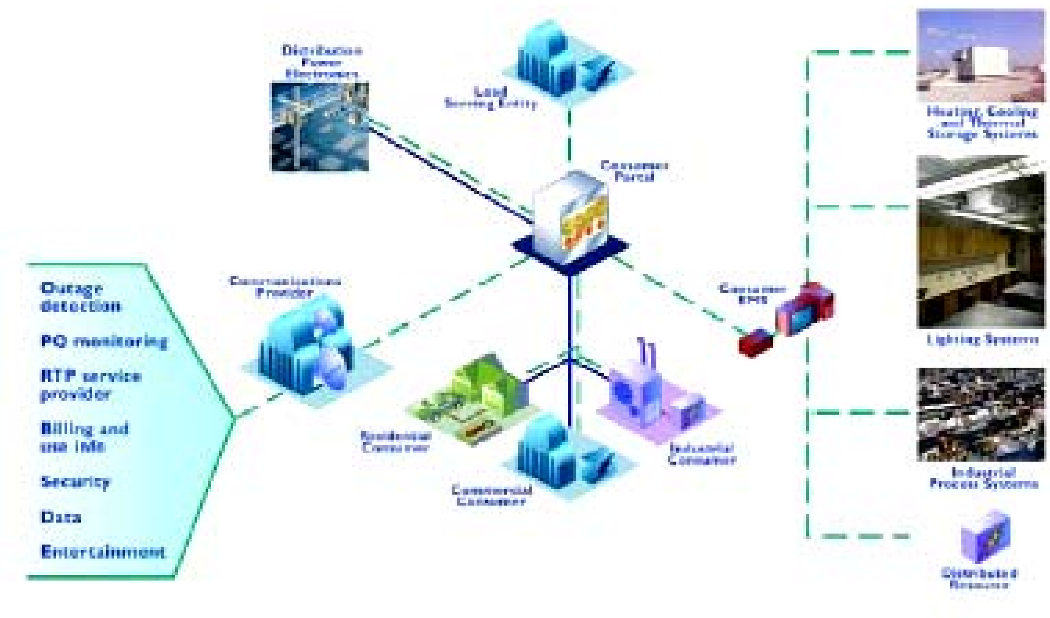

Figure 7-1
Elements of an Energy Service Portal

Key elements of developing and implementing portals include a standardized open communications architecture; appliances and other equipment that communicate with and can be managed by the portal; software applications for the consumer that enable the management of power-consuming devices; as well as a ubiquitous high-speed network backbone connecting these elements. The costs of these elements must be reduced to foster adoption, and cyber security of all elements is critical and must be addressed within each area.

The development of inter-industry cooperative initiatives with other kinds of providers will benefit the power industry by sharing development costs among many groups, and benefit the consumer by providing even more effective control of various systems. Potential collaborators include not only other utility providers such as water and natural gas companies but also broadband providers, entertainment providers, appliance and equipment manufacturers, and the many other industries whose products might be incorporated into a portal.

Standardized Open Communications Architecture

To enable the necessary communications among the many elements of the energy service portal, a universal open communications architecture is needed that accommodates the numerous protocols and standards already in place for non-energy services. Without a basic means for exchanging information among the consumer devices, the utility, and the consumer-accessible software interface, no portal functions can exist.

Prior portal pilot projects demonstrated the need for a standardized open architecture and data gateway that allows technology providers to develop equipment and applications that meet the evolving needs of utilities and their consumers. The successful implementation of energy service portals depends on seamless information exchange among applications available in the portal, the consumer devices that are monitored and managed through the portal, the electric meter, and the utility itself, which provides decision-making information directly to the consumer.

Work by the EPRI IntelliGrid Consortium has resulted in identification of potential technologies that can be used to form a reference telecommunications architecture that describes the essential elements and significant relationships within a system or environment. The goal of the reference architecture is to define key points of interoperability between devices and their environment. This is accomplished through well-defined, standardized interfaces, and suggested attributes that various vendors can use to develop products that will operate seamlessly within the portal environment. Further R&D work remains to complete the reference architecture, foster industry acceptance, and promote its implementation.

Ubiquitous High-Speed Connectivity

Energy service portals require reliable high-speed communication between the portal interface, the equipment managed by the portal, the utility, and others. A variety of possible communication media equipment may be able to meet this requirement, including wireless, broadband-over-power-line (BPL), DSL, cable, and fiber. Based on past work, the hardware chosen for local and wide-area network connectivity can greatly impact the total installed cost of energy service portal systems.

R&D is needed to identify and implement a ubiquitous cost-effective solution for a high-speed network backbone for the infrastructure as a whole, as well as the “last mile” problem of extending the network to the consumer premises. Power lines to consumer premises are much more prevalent than broadband options such as DSL and cable, especially in remote areas. Hence, to capitalize on revenue opportunities, energy companies could accelerate efforts to refine the technology, develop standards, and speed adoption of BPL.

Smart Appliances, Meters, and Other Equipment

All of the devices that communicate with, or are managed by, the portal – such as the electric meter, appliances such as refrigerators and water heaters, HVAC systems, security systems, and home entertainment systems – must be able to receive and respond to signals from the portal. Equipment must contain the necessary sensors, computing capability, and other components to handle functions such as diagnosis and repair, demand response, energy management, and rate response. These components must be designed, tested, and commercialized at a cost that is not prohibitive to the manufacturer, utility, or consumer.

Energy Service Portal Applications

A portfolio of consumer-facing software applications that deliver all the capabilities of the portal to the devices of the consumer's choice (such as Internet-connected PCs, wireless or X10 networks in the home, and mobile phones) must be developed. The applications should enable consumers to understand and manage the components under their control for functions including demand response, energy management, security, and equipment maintenance. The applications must also access and manage any available advanced information or entertainment services. R&D is required to determine the set of applications that offers the most benefit to consumers and utilities; to manage their design, development, and interoperability with equipment from different vendors; and further their implementation and promotion in the marketplace.

Reducing Implementation Costs

Economies of scale are vital to ensuring that portals are cost-effective. A 2004 study of the business case for portals by the EPRI IntelliGrid Consortium was based on potential use in California. Results showed that while the costs of implementation are high – from $200 to $600 for residential portals and $700 to $1700 for commercial and industrial portals – the potential benefits are significant. Among the many results, the study showed that a discounted cash flow analysis of the portal's top dozen benefits using a utility investment return on equity rate of 15 percent yielded a total net present value of over $15 billion – more than seven times the initial capital investment amount, or almost $12,000 per device.

Despite this potential return on investment, the current implementation costs may present a serious obstacle. Thus, to fully realize the market potential of the energy service portal, the cost of components must be reduced. R&D is required to study all of the elements that result in the high cost of deploying energy service portals and devise improvements that make these components more affordable.

Demand Response

One of the advanced energy management functions enabled by the widespread deployment of energy service portals is the effective implementation of demand response strategies. Fluctuations in consumer demand for electricity are influenced by factors such as weather, time of day, and demographics, while supply-side capacity to meet this demand is dependent on the season, weather, scheduled and unscheduled outages, as well as the ability to draw power from neighboring utilities. When consumer demand compared to supply capability approaches minimum capacity margins, utilities call on consumers to respond by reducing their demand, with varying degrees of success. The new technology opportunities enabled by an energy service portal will help consumers better understand, monitor, and make educated choices about their power usage in response to changing conditions. This will be particularly useful in scenarios that benefit from demand response, such as the "Double Whammy" scenario.

It has been estimated that portals can reduce demand by approximately 5 to 10 percent on average, and price signals can be used to return operating reserve margins to appropriate thresholds when they begin to decrease. Hence, the effective implementation of demand response can reduce the need for new power plants, transmission lines, and distribution lines, while minimizing congestion, avoiding outages, and improving reliability.

Overall, demand response offers significant opportunities to reduce power costs while improving quality of service. This section outlines selected future technologies that build upon the capabilities of the energy service portal to enable effective demand response strategies.

Automated Demand Response Integrated Platforms

Technologies already exist that inform consumers of pending electric capacity shortfalls or pricing events, help their buildings control loads in response to these conditions, and measure and report power demand in a real- or near-real-time manner. However, these technologies do not fully communicate with each other or operate in an integrated fashion. R&D is required to integrate building energy-management control systems with notification and metering systems to enable automated and effective demand response at consumer-defined thresholds with minimal intervention.

Innovations in Mass Market Direct Load Control Programs

Utilities have implemented direct load control (DLC) programs for many years. However, these programs are becoming more important because of the system constraints that many utilities face during peak power periods. The DLC systems that utilities typically deploy rely on radio-frequency control features that do not enable consumers to easily participate in load control events. R&D is required to identify technologies that enable consumers to more easily participate in load control events through improved two-way consumer interaction and response utilizing the portal.

Building- and Community-Integrated Energy Systems

The deployment of an energy service portal provides a technological foundation for the deployment of building-integrated energy systems (BIES) that enhance energy efficiency and sustainability. Reaching beyond the mere deployment of smart appliances such as refrigerators and water heaters, comprehensive BIES relies on building and infrastructure technologies that minimize the use of nonrenewable natural resources. This offers benefits that extend beyond reduced power demand to include significant environmental improvements not only for the utility but also throughout the community at large. Issues to explore for the implementation of BIES include the following:

- Integration of buildings with other buildings in the community for effective monitoring and control
- Integration of distributed generation waste heat with uses of thermal energy for selected buildings and end uses
- Distribution system technology and communication architecture that detects faults, communicates fault location, promotes interoperability of distribution system components, and facilitates use of advanced electric and gas end-use equipment
- Coordination with other infrastructure elements including communications, water and wastewater, solid waste disposal, and transportation to develop fully sustainable communities

R&D opportunities also exist in the design, testing, and commercialization of these technologies, as well as in the promotion of the sustainable-community concept.

Automatic Meter Reading

Utility costs associated with manual meter reading are affected in part by consumer density, locked doors and gates, unfriendly animals, and meters within locked areas (especially at commercial and industrial facilities). Further costs are incurred by incorporating meter-reading data into back-office operations, billing, and consumer support. Automatic meter reading (AMR), which relies on intelligent meters that can communicate usage to the utility at any time, reduces these costs and introduces a range of new benefits. These include automatic interval reading that helps establish demand peak usage and time-of-use consumption; consumer notification of unusual consumption; theft and tampering detection; and flexible consumer billing and end dates. While some advanced meters already exist, research is needed to further develop low-cost automatic meter reading capabilities and ensure their secure integration with larger energy service portal efforts.

Conclusions

The initial promise of the energy service portal is an empowered consumer who is able to make intelligent decisions about energy consumption and act upon them. Capabilities enabled by the portal, such as sophisticated demand response and automatic meter reading, will certainly improve end-user energy utilization and management. However, the possible applications of the portal extend beyond mere energy management to include a vast array of benefits to the consumer. These range from the promise of “smart” appliances that sense and diagnose their own operating condition to the potential for energy companies to leverage energy use data and serve as an integrated content and data provider through a common, easy-to-use interface.

None of the benefits of the portal can be realized without the coordinated development of a standard communications architecture, ubiquitous high-speed connectivity, smart appliances and equipment that communicate with and are controlled by the portal, and user applications that harness the power of the portal in an easy-to-use manner. In addition, the costs of these elements must be low enough to remove financial considerations as a barrier to adoption, and the data streams must be cyber secure to ensure confidentiality and safety from unauthorized (and potentially malicious) access. Additional research is needed to enable utilities and consumers to benefit not only from energy-related services such as demand response, automatic meter reading, and BIES but also from new high-value advanced information and entertainment services.

While a portal offers financial, utilization, and consumer relationship advantages regardless of the scenario, one of its most important immediate benefits is in the area of reducing demand, and therefore reducing the need for generation as well as the need to install costly transmission or distribution equipment upgrades. Besides helping address the issue of rising fuel costs, the environmental benefits of reducing demand are significant – in California alone, a 1 percent decrease in annual usage is estimated to save almost 10 million tons of carbon dioxide (CO_2) emissions.

The following describes how the potential benefits of energy service portals is likely to be most beneficial for each of the four scenarios.

- **The "Digging in our Heels" scenario.** When power costs are high because fuel prices are high, even though environmental emission costs are low, the portal enables consumers to lower their demand and their bills. In addition, the demand response and other consumption reduction capabilities enabled by widespread portal technologies will help utilities ensure an adequate supply of power without excessive costs.
- **The "Double Whammy" scenario.** Consumer energy costs are doubly affected when natural gas and the cost of CO_2 emissions are both high. In this scenario, consumers and the industry as a whole will benefit the most from demand management and reducing end-use consumption. Because of the dual factors increasing costs, this scenario will generate the greatest interest in the sustainability and efficiency improvements of building-integrated energy systems.
- **The "Biting the Bullet" scenario.** When environmental costs are high, electrical costs for the consumer will be high as well, to accommodate the expense of additional emission controls. The portal enables consumers to reduce their demand, and therefore reduce the creation of CO_2 associated with generation as well as decrease their energy costs. In addition, by supporting accurate usage prediction, demand response, and advanced grid management strategies, the portal helps utilities avoid the problems associated with transmission bottlenecks and reduces the need for costly transmission upgrades. And, an increased interest in efficiency and sustainability associated with this scenario can drive the development of building-integrated energy systems.
- **The "Supply to the Rescue" scenario.** Although fewer market participants are concerned with fuel or CO_2 costs in this scenario, which offers a generous supply of low-cost natural gas, the advanced grid and usage management capabilities offered by the portal make it possible to avoid the transmission bottlenecks associated with increased generation. As utilities seek to expand opportunities for revenue, new high-value non-energy services will be important in all scenarios. However, they will rise to the forefront in this scenario, when low power costs enable consumers to increase consumption of lifestyle-related services.

Figure 7-2 illustrates the greatest opportunities in each scenario, while Figure 7-3 illustrates the relative importance of the portal in each of these scenarios.

The energy service portal is unique among the topics discussed in this report because it is a technology with which consumers will interact on a daily basis. Its "high-touch" value provides a unique chance to ensure that consumers' perceptions of the utility evolve to view the utility as a valued partner that enables a range of previously unavailable integrated services. Utilities will benefit from expanding their consumer-utility vision to include all possibilities enabled by this unprecedented opportunity.

Key R&D Topics

Following is a list of the key R&D topics for the energy service portal:

- Integrate demand-response technologies and direct load management strategies and systems
- Integrate and demonstrate IntelliGrid technologies and building and community energy management systems
- Establish two-way, standardized, secure communication interface between utility and consumers
- Establish universal, secure communications infrastructure
- Integrate diverse range of consumer, information, security and entertainment services

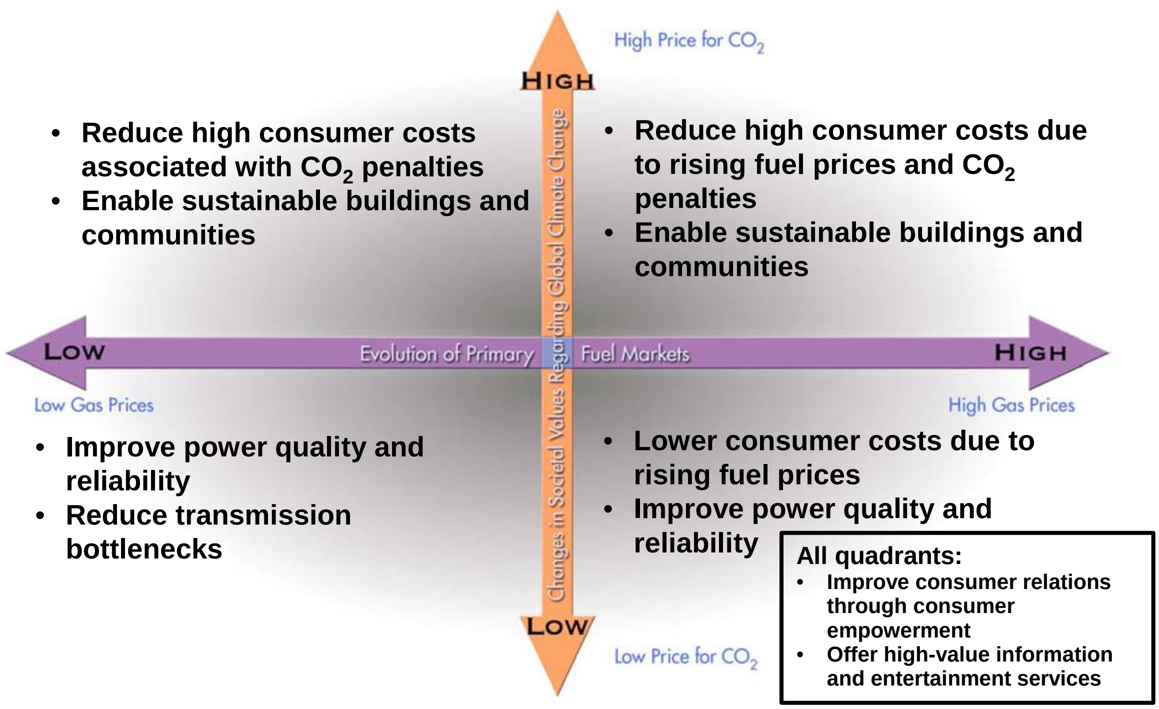

Figure 7-2
Opportunities in Each Scenario Drive Development in the Energy Service Portal

Scenario	"Biting the Bullet" High CO_2 prices; Low gas prices	"Double Whammy" High CO_2 prices; High gas prices	"Supply to the Rescue" Low gas prices; Low CO_2 prices	"Digging in Our Heels" High gas prices; Low CO_2 prices
Overview and drivers of technology R&D	Must deliver environmental benefits, and minimize associated consumer costs.	Must deliver environmental benefits, and minimize consumer costs associated with increased CO2 penalties and high fuel prices.	Must deliver new benefits to consumer, and enhance utility operations.	Must reduce consumer costs associated with high fuel prices, and enhance utility operations.
Technology R&D Gaps: For each scenario, these represent the critical technology R&D needs in the area of the energy service portal.	Integrate all basic portal elements (communications architecture, connectivity, smart equipment, consumer applications) — Very critical	Very critical	Very critical	Very critical
	Integrate demand response technologies and direct load management strategies — Very critical	Very critical	Critical	Very critical
	Integrate and demonstrate building-integrated energy systems — Very critical	Very critical	Critical	Critical
	Integrate automatic meter reading — Critical	Critical	Very critical	Very critical
	Integrate range of consumer, information, security, and entertainment services — Critical	Critical	Very critical	Critical

Legend:
Very critical (solid red arrow)
Critical (dashed orange arrow)
Important (dashed blue arrow)

Arrows indicate that the R&D need applies to *more than one scenario*

Figure 7-3
EPRI Scenario and Technology Development Matrix for Energy Service Portal

End-Use Energy Efficiency

Overview

Technology innovation in electricity use has been the cornerstone of global economic progress for more than 50 years. The growth in U.S. Gross Domestic Product has been accompanied by simultaneous improvements in energy intensity and labor productivity. At the same time, the proportion of energy use attributable to electricity has increased. This is no coincidence. Prosperity and growth in electricity dependence have been the result of electricity's unique ability to satisfy precise and high value applications of energy.

There are a host of compelling reasons for developing and deploying end-use energy efficiency (see Figure 7-4). For example, an aggressive national program to reduce greenhouse gases needs to include enhanced end-use energy efficiency, if Kyoto-level or even lower level improvements are to be approached. Additional environmental benefits, such as reducing chemical discharges, alleviating combustion products, and others, result from electricity-based substitution for non-electric based processes. Energy efficient technologies are a resource for reducing energy use and consequently reducing peak electrical demand. Energy efficiency and demand response (load management) are complementary tools that can be used with distributed resources to **alleviate** transmission, distribution, and generation **capacity constraints**; and new technologies to improve consumer electricity-use efficiency are effective in reducing the **need for additional generation**, **transmission, and distribution capacity**.

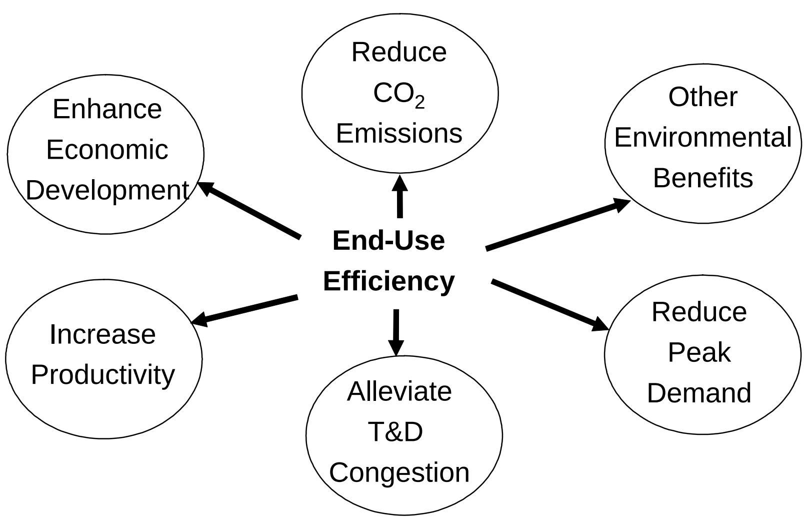

Figure 7-4
Benefits of Improved End-use Efficiency

At the same time, energy-efficient technologies can help industrial consumers be more productive, and profitable. For example, by replacing inefficient electric processes, chemical processes, and combustion processes, efficient electric processes save costs and improve the environment. Deployment of high-efficiency electrotechnologies can also be an effective means of achieving **economic development** and **consumer retention** objectives. Further, efficient electric technologies can help **reduce the dependency on foreign oil for that part of the generation mix using oil fired generation.**

Traditional targets for improved energy efficiency include lighting, motors, and heating, ventilating, and air conditioning (HVAC) systems, most of which consume more energy than necessary. In developed countries, for example, artificial lighting alone consumes 20 to 25 percent of all electric energy. Opportunities for savings in the industrial sector are also significant.

Because the topic of end-use energy efficiency is so broad, the following sections focus on a sampling of areas that offer significant across-the-board benefits. Additional R&D opportunities for specific industries and applications should also be pursued.

Improved Industrial Processes

The economic prosperity of an electric utility and the communities it serves is often inextricably linked to the vitality of its industrial consumer base. Industrial enterprises are under constant pressure to drive down operational costs while also improving product quality in order to compete in the global marketplace and reducing environmental impact. The downscaling or closure of an industrial facility can devastate a town’s social and economic base, and result in a significant loss of load and revenue for an electric utility.

Recognizing this relationship, many electric utilities have sought ways to retain their industrial consumers by helping them become more competitive. Electrotechnologies rely on the inherent advantages of electricity to yield well-documented benefits for industrial energy users, including the following:

- Improve local economic conditions by reducing facility operating costs, improving product quality and productivity, enhancing the environment, and increasing profitability.
- Significantly reduce greenhouse gas production and provide an economic alternative to very tight control of power plant emissions
- Offset the need for added power plant capacity
- Sustain growth of the gross domestic product and improve energy intensity, thereby enabling national prosperity.
- Reduce U.S. dependence on foreign oil supplies and improve U.S. energy security

Depending on the specific industrial application, energy use trends vary widely; however, some general R&D needs are consistent across many industries. These technology gaps need to be closed by developing advanced energy efficient technologies, increased waste heat and material recovery, improved controls, and enhanced energy management practices.

Because of the number and diversity of industrial processes, space limitations prevent discussion of all potential efficiency improvements for all sectors. Instead, this section covers some of the most critical R&D needs for improvements in processes common to a number of industries, and for specific industries such as aluminum processing in which energy consumption accounts for a significant portion of the nation's overall energy use.

Cross-Industry Process Improvements

The following is a sample of promising R&D opportunities to improve the energy efficiency of processes that are common across many industries.

Motor Systems

Because electrically driven equipment accounts for about 67 percent of industrial electricity use in the United States, the efficient use of motors and drives presents a considerable opportunity for energy savings. In fact, a U.S. Department of Energy (DOE) study for the Motor Challenge Program showed that applying cost-effective measures (three-year simple payback) in the industrial sector would yield energy savings of 70 to 100 billion kWh/yr (10 to 15 percent of annual industrial motor electricity use). Hence, efforts are needed to develop cost-effective, high-efficiency motors for niche markets where high-efficiency motors with suitable application characteristics do not exist, and to further the acceptance of high-efficiency motors that are already available on the market.

Because the proper application of adjustable speed drives can often cost less than replacing an older inefficient motor with a newer energy-efficient motor, furthering the design of adjustable speed drives may be one of the most rewarding areas for research. Candidate technology improvements include the development of low-cost adjustable speed drives for small and medium-size motor applications, adjustable speed drives with smooth torque at rated output, "self-tuning" adaptive controllers, soft switching for alternating current applications, universal adjustable-speed drives; and reliable adjustable-speed drives for DC applications with lower sensitivity to voltage sags and spikes. Technologies like these that reduce electricity consumption in applications that already use electricity are particularly attractive in scenarios that require efficient electricity use to help minimize environmental impact.

Freeze Concentration Processes for Solids/Water Separation

Separating solids and water is a key component in many industries, including metals fabrication, pulp and paper, and food processing. Separation has typically relied on chemical flocculants and gravity, or thermally-driven processes such as distillation; and, more recently, membranes (which can require a significant amount of energy.)

Electric freeze concentration and separation processes, which present a potential alternative to chemical and combustion/thermal processes, rely on refrigeration. As an ice matrix is formed, impurities are pushed from the mixture, resulting in the separation of the water and solids. Advanced separation systems using freeze/thaw treatments could be operated at approximately 30 to 50 percent of the cost of conventional separation systems, such as thermal distillation, when disposal costs such as brine disposal are included in the analysis. Lifecycle costs for a freeze/thaw system are estimated to be approximately 60 to 80 percent of the costs of existing, conventional systems. Research is needed to develop and test prototypes capable of fully realizing the potential of widespread freeze concentration systems.

Microwaves for Drying and Heating

Microwave processing, which is an emerging technology suitable for replacing conventional combustion and electric heating, offers advantages such as accelerated drying times, increased production rates, reduced energy costs and floor space, and enhanced product quality. These benefits are a result of the technology's inherent adjustability, and the ability to apply microwave heating to specific targets. Total savings will depend on the application, but laboratory estimates show that microwave drying and heating processes can reduce costs by as much as 75 percent compared to conventional heating methods.

Before microwaves can become a viable industry alternative, two critical capability gaps must be addressed. First, because more energy is currently required to generate microwaves or radio frequency waves than to generate steam, improvements in magnetron energy efficiency are needed. Second, most microwaves currently available are designed for consumer use and deliver a non-uniform heating pattern; hence, additional research into microwave oven design to deliver a uniform heating pattern is required. Research and testing in these areas is necessary to realize the potential benefits of microwave drying and heating for industrial processes.

Low Temperature (Non-Thermal) Plasmas for Air Treatment

Non-thermal plasma technologies (NTPs) are advanced oxidation processes that can be used to destroy a wide variety of air pollutants, including nitrogen oxides (NO_x), sulfur dioxide (SO_2,), volatile organic compounds (VOCs), heavy metals, and other toxic air pollutants. Electric energy is applied to a bulk gas to produce plasmas, which generate a wide variety of active oxidizers and reducers. One advantage of these techniques compared to high-temperature plasma technologies is that less energy is required to achieve the same degree of chemical activity.

NTP technology could potentially be used for air pollution control in metals processing, chemicals and petroleum, and forest products industries, as well as to improve indoor air quality in urban environments. Once established in the marketplace, NTP technologies are projected to be an estimated 30 percent less expensive than the conventional technologies they replace, such as incineration or oxidation technologies, and paybacks on replacing existing technologies with NTP technologies should be less than one year. In scenarios where environmental issues are a significant concern, NTP technologies are an attractive area of research given their wide potential in environmental applications, and their potential to replace more passive technologies, such as catalytic destruction.

However, some barriers to wide-scale deployment of NTPs currently exist. First, additional research is required to address limits in scalability, which result from the relationship between the reactor size and electrode system, particularly for the destruction of NO_x from high gas flows. And, because some evidence suggests that NTP byproducts may include dioxins and furans, further research is required to address whether such byproducts exist and how they should be addressed.

Recycling Technologies

A variety of opportunities exist to improve industrial and urban ecology, including water reuse, pollution prevention and recycling, and clean manufacturing technologies. For example, better separation and automated sorting equipment is needed to enhance recycling of plastics. Clean manufacturing technologies include closed loop aqueous cleaning, waterborne wood finishing, closed-mold fiberglass reinforced plastics, dry machining, and waterborne adhesives.

Industry-Specific Improvements

Each industry presents opportunities to develop energy-efficient technologies that match their unique requirements. However, specific attention is needed in industries where energy use is intensive or that present special strategic value to the country.

Aluminum and Steel Industries

Energy use in the aluminum industry is significant – roughly one third of the cost of aluminum results from energy consumption. However, recovering scrap substantially reduces energy use; in fact, aluminum produced from recycled scrap requires only about five percent of the energy required to produce aluminum from bauxite. While the efficiency of the reduction process has increased greatly as a result of improved cells and reduced electrical resistance losses, potential remains for even higher efficiency in the form of advanced reduction processes and new anode and cathode materials to replace carbon. In addition, process heat applications, which account for 23 percent of end-use energy, would benefit greatly from efficiency improvements. Other efficiency opportunities include heat recovery, improved controls, and continuous casting in the place of batch casting.

In the United States, roughly 12 to 15 percent of the cost of producing steel corresponds to energy costs. In fact, between 1975 and 1994, the United States steel industry reduced energy use by 45 percent and significant energy efficiency efforts are still underway. Opportunities in the steel industry include increased furnace efficiency, process modifications (i.e., continuous versus batch casting), heat and power recovery, and cogeneration.

Petroleum Refining

Petroleum refining accounts for about 7 percent of U.S. energy use, of which two-thirds of the energy is used for heat and power (mostly from petroleum). Using advanced electrotechnologies, the energy content in the petroleum can be used more effectively and the energy required to process petroleum could be reduced. For example, the use of specially-designed membranes could reduce the energy requirements of distillation by 20 percent. Other process technologies that can improve chemical and petroleum facility production include microwave technology to selectively target heating to improve the effectiveness of chemical reactions; electrochemical synthesis to treat process waste streams and enhance the manufacturing of value-added chemicals; electro-separation to enhance chemical or physical separations; laser chemistry to direct process paths; and ultrasonic chemistry to improve reaction rates.

Advanced sensors, controls and process optimization software could further reduce energy use, reduce wastes, and increase production by more effectively using petroleum. For example, utilizing advance control and power technologies in the oil-refining industry, including variable speed drives, fuzzy logic, and neural network control algorithms, could potentially save approximately $1.5 billion annually in energy costs (principally petroleum). Additional benefits include reduction in operating transients, and elimination of maintenance-prone inefficient hydraulic components and steam turbines.

R&D opportunities exist in the design, testing, deployment, and support of this range of new electrotechnologies to improve efficiency in petroleum refining.

Commercial and Residential Improvements

R&D into high-efficiency electric technologies for commercial and residential use can result in lower operating costs as well as environmental benefits. As in other areas, only selected important opportunities are described here.

Lighting

Lighting is a major electricity use, accounting for approximately 23 percent of national electricity consumption. Of the common lamp types, incandescent lights dominate residential usage, and tubular fluorescents and high intensity discharge (HID) account for 2/3 and 1/3 of commercial usage, respectively. Industrial usage includes both fluorescent and HID lamps, while street lighting is largely HID-based.

Opportunities exist for improving incandescent lamp efficiency using an innovative microscopic tungsten lattice structure to boost filament efficiency from 5 percent to about 60 percent (from 15 lumens/watt to 180 lumens/watt). Fluorescent lamp efficacy goals of 200 lumens/watt (compared to current efficiencies of 120 lumens/watt) are being sought using high-efficiency emitters that are environmentally benign, as well as using phosphors that emit two visible photons for every one invisible photon collision. Efforts are underway to improve HID lamps from 75 lumens/watt to 150 lumens/watt by shifting output from the infrared to the near-ultraviolet or visible emission.

Light-emitting diodes (LEDs) offer the potential of a versatile, general illumination light source with efficiency of 200 lumens/watt. Efforts are underway in the areas described above but are in need of increased funding to achieve timely results. More efficient, well-designed lighting can improve the productivity of industrial and commercial establishments, making them more profitable, and growing the local economy. More efficient lighting can also reduce peak demand and offset the need for added electric generation, transmission or distribution capacity.

Another crucial area is lighting controls. While efficient lighting controls can improve efficiency and productivity (in commercial environments), technologies such as occupancy sensors, photo sensors, and dimming controls all currently have low market penetration. Reasons include cost and complexity, lack of viable alternatives for retrofit technologies, and difficulty in the installation, integration, and operation of photosensor technology and controls. Research needs in this area include the development of retrofit lighting controls to achieve fluorescent lamp dimming (i.e., low cost dimmable electronic ballasts); instant-start load shedding ballasts for fluorescent lighting systems; and the development of photosensor and lighting control systems optimized for common situations. Market transformation (i.e., incentives to adopt lighting controls) is also needed in this area. (Additional information on research needs in lighting control systems appears in the section on the energy service portal.)

Heating, Ventilating, and Air Conditioning

Heating and cooling devices account for more than 50 percent of the on-site energy use – and over one-third of the electricity used – in residential and commercial buildings. Space cooling and refrigeration systems are primarily electricity-powered systems, while space heating is largely provided by non-electric systems. Substituting highly efficient electric-based alternatives for natural gas-fueled space heating is particularly attractive in scenarios with high natural gas prices.

Advanced heating, ventilating, and air conditioning (HVAC) options can be used to shape loads, augment revenue, enhance local economic development, increase consumer satisfaction, improve the environment, and provide economic alternatives to supply-side options. Utility consumers benefit from reduced energy bills, improved living and working environments, and greater productivity and health.

Fundamental research is needed to address a wide range of topics related to HVAC systems. These areas include heat pump water heaters, heat pump technologies, ventilation /indoor air quality, and space heating and cooling. Efforts are needed to increase the knowledge base in each area, identify and characterize the best available electric technologies for applications of interest, clarify what improvements are needed to compete with alternative technologies, and undertake efforts to develop and demonstrate improved technologies that enhance competitiveness of electric heating and cooling options.

An important research objective is to develop cost-effective, factory-built air conditioners and heat pump systems with substantially higher efficiencies compared to current sales-weighted Seasonal Energy Efficiency Ratios of about 10.8 and Heating Seasonal Performance Factors of about 7.1. Heat pumps with better low temperature performance, better defrost performance and higher discharge temperatures are also needed. Achieving these improvements will require innovations that might include enhanced heat exchanger surfaces, new refrigerants, variable capacity compressors, refrigerant charge management, sub-cooling, higher efficiency motors, smart sensors and controls.

Office Technologies

In 1999, office equipment was estimated to account for about 2 percent of U.S. electricity use; however, office technology energy use is growing rapidly and is expected to account for more than twice this amount by 2011. Promising research opportunities for keeping office technology electricity use in check, while encouraging continuing increases in information technology capability, include the following:

- **Computer data centers.** The speed at which new data centers are built results in a number of issues. The short lead time and magnitude of the service requirements can create problems for the serving utility, which are exacerbated by the haste of the building process and the selection of expedient but inefficient equipment. A more thoughtful approach could result in better estimation of electric service requirements, more efficient HVAC equipment, incorporation of more efficient power supplies and even a DC power distribution system. Cooperative research between utilities and data center developers to create a model data center that improves efficiency and reduces costs for the data center while simultaneously reducing load requirements will benefit all participants.
- **Power supplies.** Potential improvements in pulse-width modulated switching power supplies include addressing the losses attributable to conduction switching, rectification, and magnetic components with techniques including snubbers, resonant converters, and active clamps. Efficiency improvements to switch-mode power supplies include digital control techniques, electronic transformers, integrated components and materials packaging, improved magnetic materials, and improved capacitors.
- **Computers.** One of the drivers for increasing U.S. productivity has been the reliable improvement in computing power, speed and cost in the 1980s and 1990s. More effective cooling solutions will be needed as power densities and cooling requirements continue to increase geometrically in the future. Potential technologies include spray-cooling electronic equipment with a volatile dielectric fluid using miniature atomizer arrays, or the use of higher conductivity silicon. More advanced cooling concepts include thermal pastes or nanotechnologies such as microgroove heat pipes.

- **Monitors.** Replacing liquid crystal displays (LCDs) with organic light emitting diodes could result in clearer displays that are up to 66 percent more efficient at half the cost. However, additional research is required to sustain color over time. Other potential display technologies include field emission, electro-luminescence, and gas plasma displays, as well as cholesteric LCDs.

Household Appliances

Efficiency improvements in household appliances can be achieved in the following areas:

- **Water heaters.** The electric vapor compression (heat pump) cycle can increase the efficiency of the water heating process by a factor of 2.5 or more, but this cycle is not widely adopted. Possible barriers to market transformation include high initial costs, lack of familiarity with the technology, limited choice of manufacturers, inconsistent reliability, and improper sizing. Addressing these issues can result in significant residential efficiency improvements and lower operating costs than natural gas-fired water heaters, especially in scenarios with high gas prices.
- **Cooking.** Many recent advances in cooking efficiency, such as ovens that combine microwave and convection technologies for faster, heat-efficient baking, have resulted in expensive equipment that is not widely adopted. However, an advanced technology that can increase efficiency and reduce product cost is the induction cook-top. This and other technologies that improve efficiency, reduce capital equipment costs, and offer other cooking benefits are required to help ensure market adoption.

Market Transformation Issues

For all new end-use technologies, market transformation is a significant issue. Industrial energy efficiency technology development programs need to incorporate market transformation and market connection elements to assure that these technology development efforts result in maximum market penetration of the commercialized technology. These efforts should be organized to include the following activities: understanding the influential participants in the market infrastructure, their roles in the market, and drivers that they consider important in considering new technologies; identifying market barriers that inhibit market penetration of new technologies and actions needed to overcome these barriers.

Decision makers tend to favor systems and technologies that have performed well in the past. As such, there often exists a very substantial resistance to change. Information needs to be provided to overcome this resistance to change, minimize performance uncertainties, and reduce the extra effort and consequent cost of deploying new technologies. Different decision makers have different roles in the specification, supply, and funding process/value chain. Specific market interventions will need to be designed to address the market barriers influencing the decisions of each decision maker and market participant.

Because decision makers are often not driven to make decisions based purely on energy efficiency or cost, it is likely that products will need to possess additional attributes that address the needs of key market participants. Examples of these additional benefits include improved controllability in industrial and commercial applications, and enhanced cooking capabilities and gentler clothes handling in residential applications. Incorporating market transformation efforts into technology development and commercialization efforts will greatly enhance the opportunity for the new technologies and products to achieve market success.

Conclusions

Aggressive promotion of the environmental, economic, and security benefits of energy efficiency coupled with energy-efficient products that maximize industrial and commercial consumers' returns on investment and satisfy residential consumers' primary needs could increase the market penetration and associated benefits of energy-efficient electric technologies. The ability of energy efficiency to contribute to so many objectives assures the continuing relevance and value of development efforts. Across the various scenarios, some of these value propositions will increase in importance and others will decline. But clearly, end-use efficiency provides value across all of the four scenarios.

These potential improvements in industrial, commercial, and residential end-use efficiency can be categorized in the following three areas (see Figures 7-5 and 7-6):

- Electric substitutes for non-electric processes (e.g., natural gas-fired processes) reduce fuel costs. These advances are particularly crucial in scenarios where natural gas costs are high (i.e., the "Double Whammy" and "Digging in our Heels" scenarios). In the residential and commercial sectors, examples include efficient electric heat pump water heating as an alternative to gas-fired water heaters; and electric heat pumps to replace gas-fired space heating. In the industrial sector, using microwaves instead of combustion processes for drying and many more applications fit this profile.
- Advanced electric substitutes for conventional electric technologies improve efficiency, which is particularly important in the "Double Whammy" and "Biting the Bullet" scenarios. These highly efficient electric substitutes include lighting, space cooling, refrigeration, office technology, and many others.
- In some cases, environmental protection is the primary driver for substitution of electricity-driven applications for non-electric ones. For example, substitution of a highly efficient end-use electric process, combined with "clean" central station or distributed power generation can reduce CO_2 emissions, compared to previous systems and processes. In other cases, substitution provides other environmental benefits, such as reduced impacts on water, land, or air. For example, efficient electric technologies can be used to reduce chemicals and combustion products in industrial processes. Efficient electrotechnologies such as membranes and non-thermal plasmas (low-temperature oxidation) can be used to purify water and air through separation and oxidation processes. These are most critical in scenarios where environmental issues are at the forefront of consumer efforts and legislation (i.e., the "Double Whammy" and "Biting the Bullet" scenarios).

Key R&D Topics

Following is a list of the key R&D topics for the area of end-use efficiency:

- Develop and demonstrate increased efficiency ventilation, heating and cooling systems
- Develop and demonstrate advanced lighting sources and more efficient lighting systems
- Develop and demonstrate cost-effective electro-technologies for improving industrial processes
- Develop and demonstrate increased efficiency motors and drives
- Develop and demonstrate efficient DC computer data centers and DC microgrids
- Develop improved compressors, components, refrigerants and cycles; advanced district heating and cooling systems; and magnetocaloric and thermoelectric cooling
- Assess opportunities for improved residential and commercial appliances, including advanced office equipment and smart household appliances
- Integrate IntelliGrid technologies into the existing electricity infrastructure

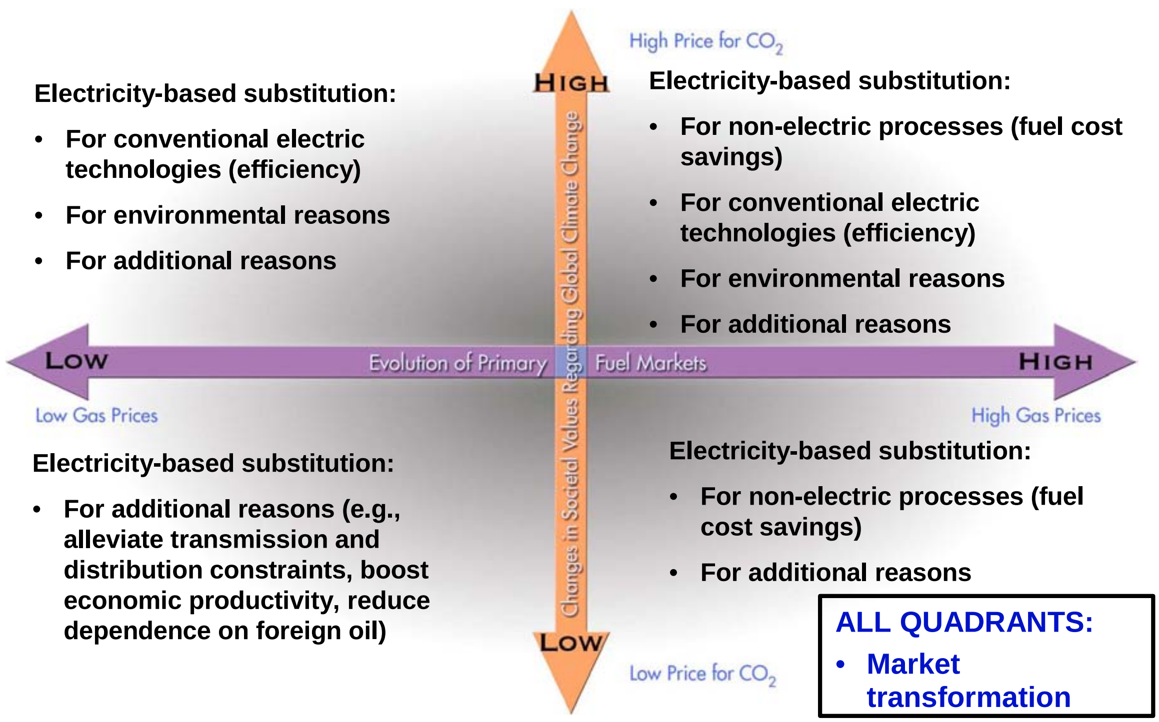

Figure 7-5
Electricity-based Substitution Can Adopt a Variety of Forms.

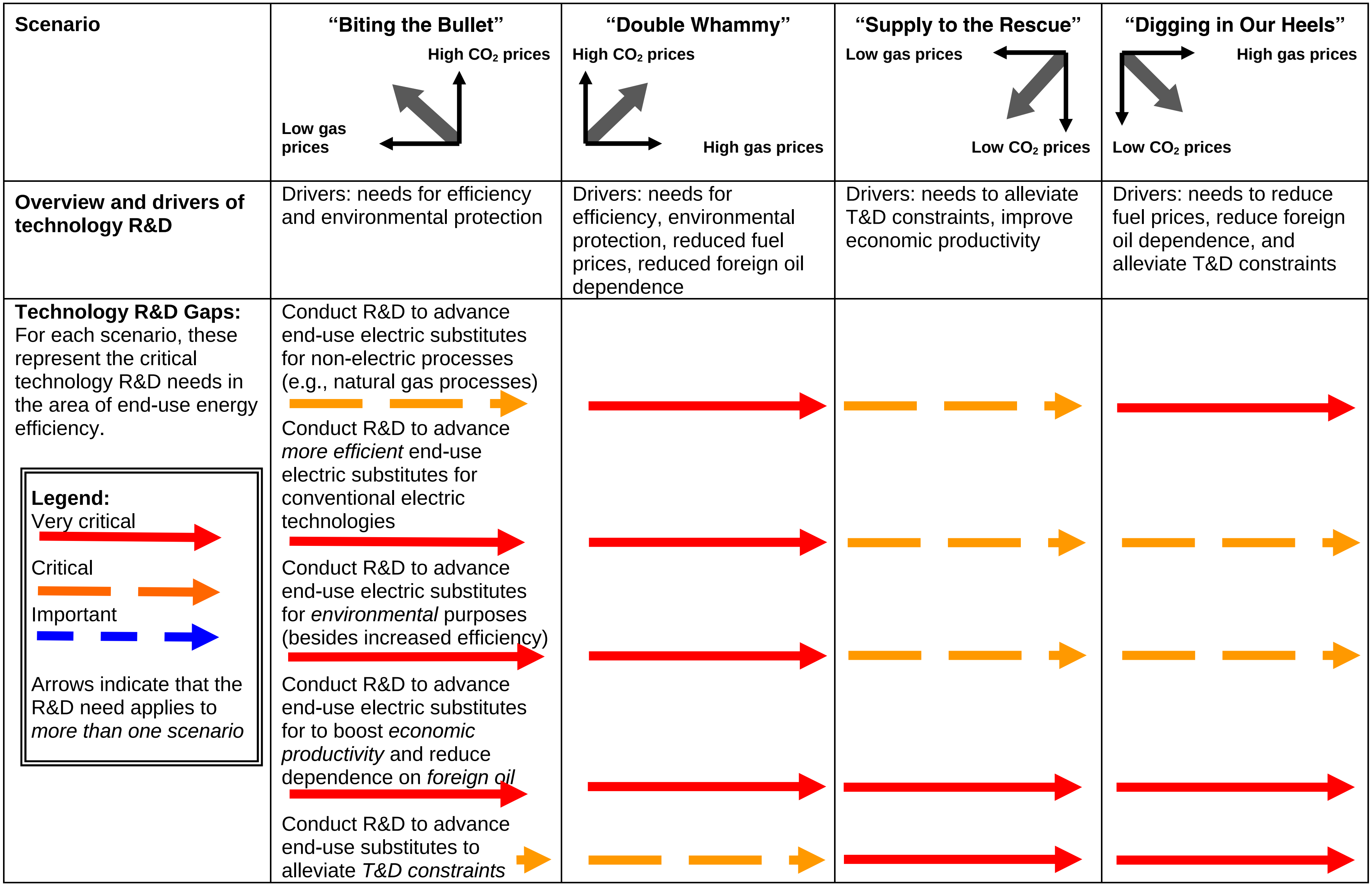

Figure 7-6
EPRI Scenario and Technology Development Matrix for End Use: Energy Efficiency

Electricity-Based Transportation

Overview

Conventional transportation (e.g., automobiles, trucks, and buses), which is the dominant mode of transportation in the United States, poses air quality concerns in congested traffic areas where carbon dioxide from automobiles mixes with diesel emissions from trucks. This form of transportation relies on petroleum-based gasoline that is increasingly expensive and primarily available from unstable parts of the world. Reliance on a critical resource – a significant portion of which must be imported – is a strategic vulnerability; minimizing dependence on foreign oil without adversely affecting the economy is necessary to ensure national security.

Electric-drive vehicles (EDVs) – a family of vehicles that includes any type of automotive transportation that relies all or in part on electric power for propulsion – present an environmentally friendly alternative to conventional vehicles that can help foster independence from the uncertainties of foreign oil. Besides offering exceptional fuel efficiency and reduced emissions to consumers, market acceptance of EDVs will enable the power industry to become a primary provider of transportation power.

The first commercially viable EDV is the conventional hybrid electric vehicle, which uses battery power to supplement the power of its internal combustion engine. Because the batteries are charged through the capture of kinetic energy from regenerative braking, these vehicles do not rely on electricity from the power grid. These automobiles represent an essentially mature technology, and no long-term R&D is required.

The next generation of EDVs is the plug-in hybrid electric vehicle (PHEV), which uses a charging system and an advanced battery to collect and store electricity from the grid. While PHEVs also use liquid fuel to ensure a longer driving range, they rely much more on electric power than the current conventional hybrids to deliver greater gasoline economy. At current U.S. energy prices (a national average cost of gasoline at $3 per gallon and a national average cost of electricity at 8.5 cents per kilowatt hour), a PHEV could run on the equivalent of 75 cents per gallon. Figure 7-7 shows the comparative fuel economy of conventional vehicles, conventional hybrids, and PHEVs. In addition, because PHEVs minimize tailpipe emissions, their widespread adoption will reduce the amount of carbon dioxide (CO_2) and other urban pollutants released into the atmosphere from automobile exhaust.

PHEVs have the potential to serve as distributed energy resources. The potential availability to the grid of millions of PHEVs (assuming that the vehicles can be managed and controlled appropriately) can enable a range of useful services for peak demand, spinning reserves, emergency power, or power management services. Figure 7-8 shows that power generation capabilities in California, for example, can easily support the overnight recharging needs of 5 million PHEVs.

While PHEVs are available as demonstration prototypes today, R&D is required to bring to maturity lower-cost high-efficiency advanced batteries, to optimize mechanical and electronic control systems that improve vehicle performance, and to shift the fueling paradigm to focus on the deployment of residential charging infrastructures in new and existing houses.

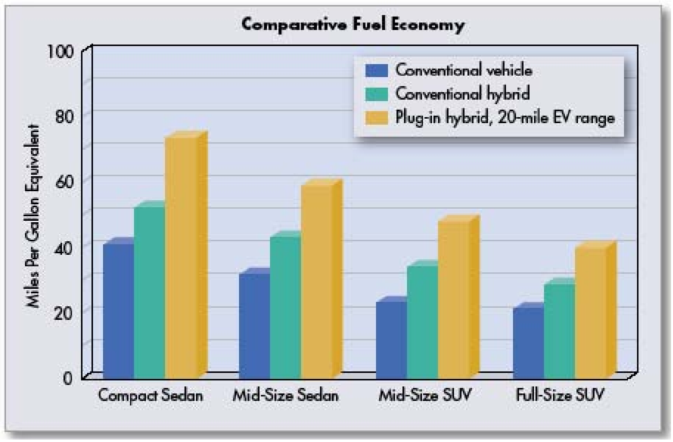

Figure 7-7
Comparative fuel economy of conventional, conventional hybrid, and PHEVs in a variety of size ranges. Photo courtesy: *EPRI Journal.*

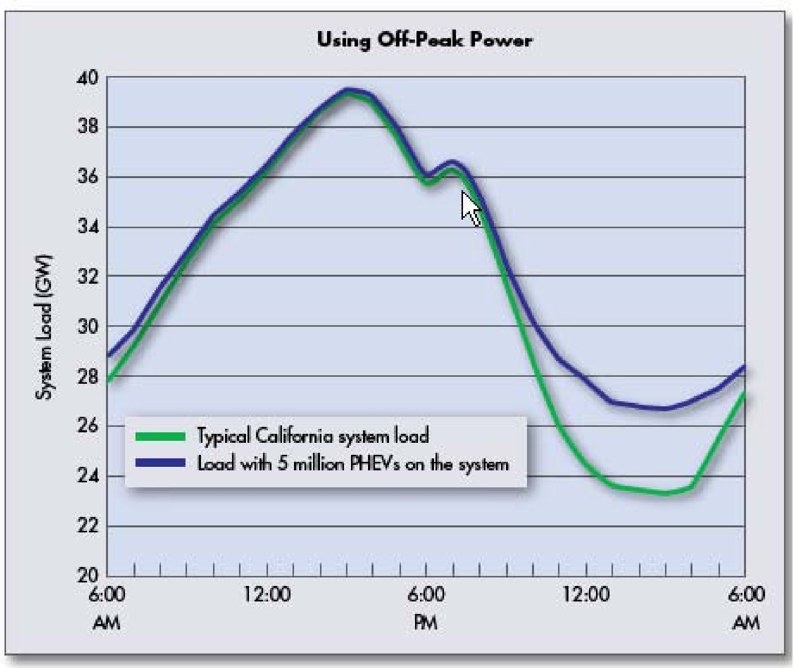

Figure 7-8
Power generation capabilities in California can easily support the overnight recharging needs of 5 million PHEVs. Photo courtesy: *EPRI Journal.*

Beyond PHEVs, further reduction in dependence on foreign oil can be achieved via battery-electric vehicles (BEVs) that rely entirely on electric power. While some all-electric vehicles already exist, BEVs will not be commercially successful until they can meet consumers' needs for driving range and performance as well as cost-effectiveness. An electric automobile that can drive for 100 miles without a recharge is within technological reach. However, R&D is needed to validate the advanced batteries and other systems to reduce costs and realize the vision of grid-dependent – and not gasoline-dependent – vehicles.

Federal, state agencies and private sector automotive and fuel cell companies are making a significant research investment to prove the viability of fuel cells as an energy source for transportation vehicles. The driving issues remain the cost and reliability of the fuel cell systems in the vehicles themselves and the high cost of the infrastructure to ensure fuel availability for initial market entry consumers and for a future large market penetration. Over the last few years, increased funding has produced encouraging progress in hydrogen used as a non-CO_2 producing fuel (since its combustion product is water vapor) for fuel cell vehicles.

The following sections describe the major R&D opportunities in the areas of electricity-powered transportation.

Advanced Batteries

The key challenge in creating marketable EDVs is the maturation of advanced batteries that enable the vehicles to compete with conventional automobiles in terms of performance, cost, and convenience. In general, the R&D opportunity is to validate currently available advanced batteries that combine high specific energy and high specific power with long life and low cost.

Today's advanced batteries, principally lithium ion (Li-ion) and nickel metal hydride (NiMH) batteries, are superior to conventional lead-acid batteries in terms of higher energy storage and power delivery capabilities; and they have longer life in the deep-discharge cycling required for EDV propulsion. However, a major disadvantage of these advanced batteries is their current high cost in vehicle applications. Both Li-ion and NiMH batteries are more costly to produce today than lead-acid batteries, because the materials are more expensive, the manufacturing methods are more sophisticated, and limited manufacturing demand fails to justify investments in labor saving automation. Because the cost of advanced batteries is expected to decrease as they enter mass production and as worldwide market competition develops, the cost challenge can be met by increasing field testing of the current pre-production technology and identifying and addressing the factors that impact cost. The cost-effective "tipping point" for advanced batteries using today's technologies is estimated to be between 20,000 and 100,000 battery packs annually. Figure 7-9 shows the projected decline in battery costs as automated manufacturing and production economies of scale are reached.

One way to reduce manufacturing costs is to ensure that advanced battery designs are applicable to more than one EDV type. R&D is required to develop commonality among battery designs, materials, and systems, with the goal of increasing the manufacturing volume of a limited number of designs and increasing the production volume of common critical materials. To this end, R&D must bring current technology to maturity and develop new battery materials for negative and positive electrodes and electrolytes that work well with the standard design families. (Separators and conductors may be an area for R&D as well.)

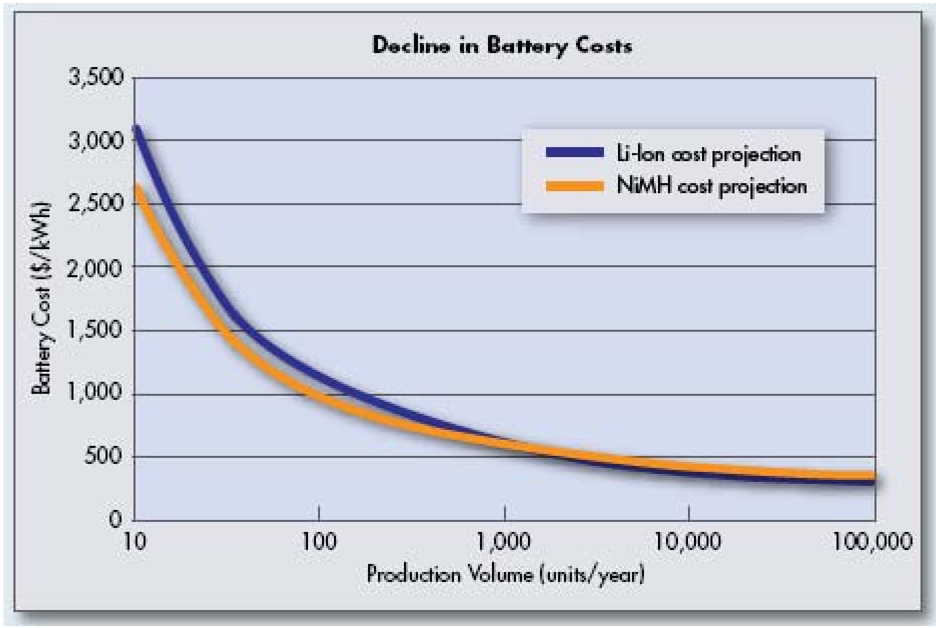

Figure 7-9
Projected decline in battery costs as production volume increases. Photo courtesy: *EPRI Journal.*

An area with long-term potential to substantially reduce battery costs is the development of less expensive materials. This is particularly true for the Li-ion electrochemical system, for which many materials may potentially be considered for use as positive and negative electrodes, electrolytes, and separators. R&D is needed to identify less costly new materials and improved materials production processes to support the use of new materials in advanced battery systems.

Beyond reducing the cost of existing advanced batteries, a further challenge is to improve the efficiency of the technologies themselves, as more robust batteries will enable PHEVs with greater range and are necessary to insure the commercial viability of an all-electric BEV. A critical capability gap in advanced battery performance is the ability to perform a large number of deep cycles. R&D is required to test current state-of-the-art batteries to identify the factors limiting deep-cycle life; apply improvements in battery operation and control; develop new designs and materials to increase calendar and cycle life; and field test the improved batteries. Key elements of this research should include a better basic understanding of life-limiting processes; the development of battery materials that are less subject to corrosion and deterioration at the prevalent operating conditions of EDVs; and the creation of control strategies and algorithms that minimize degradation processes.

Vehicle Controls, Mechanical Systems, and Power Electronics

Efficient PHEV operation relies on effective utilization strategies for gasoline and electric power. The vehicle control system requires high-level control algorithms that optimize performance and efficiency while maximizing battery efficiency and durability. In addition, the control system must be able to manage the energy storage system so that it can operate during extreme temperatures and demanding driving conditions without reducing overall battery life. R&D is required to identify optimal control strategies for a variety of operating conditions and to design control systems and supporting algorithms that respond to changing conditions appropriately.

Improvements in motor systems are an important R&D area, as PHEVs will require very high-power-density motor systems with high efficiency and minimal drag torque. A peak-to-continuous torque ratio of at least 3:1 is desired so that the electric traction system can power the vehicle under most brief transient conditions and avoid unnecessary engine engagements when the battery system is sufficiently charged. R&D is required to develop high-efficiency motor systems that maximize drive and regenerative braking efficiencies and reduce the size requirements of the battery while ensuring acceptable performance and efficiency.

Overall, commercialization of PHEVs will require a mature U.S. industry for manufacturing low-cost, high-performance electric motors and the power electronics to drive them. R&D is also required to develop low-cost, reliable production motor inverters, alternating current to direct current (AC-DC) voltage converters, and other types of power electronics that are crucial to effective PHEV operation.

Charging Systems and Associated Applications

Market acceptance of PHEVs and BEVs demands a safe and usable set of charging standards that will enable vehicle charging that is as easy as cell phone charging. Ideally, a passenger vehicle requiring 4 to 7 kWh should be able to fully recharge in four to six hours with 110 VAC, while a larger commercial van requiring 14 to 16 kWh could recharge using 220 VAC, which is widely available in commercial and industrial facilities. The R&D requirement for individual on-board chargers is to reduce manufacturing costs sufficiently to ease commercialization. Additional R&D is required to develop standards and technologies for charging systems.

In the longer term, R&D is needed to ease and automate the charging process. For example, automatic recharging systems that deploy as soon as a vehicle is parked would free consumers from worrying about whether they remembered to plug in their vehicle. Such systems reduce the possibility of driving on an uncharged battery, which decreases the fuel economy of PHEVs. R&D is needed to design a standards-based automated recharging system for both vehicles and the garages in which they are housed. In addition to integrating such systems into new residential construction, cost-effective retrofitting of charging systems into existing homes is needed as well.

If the vehicle charging system is integrated with the home electrical system, then power could flow from the vehicle battery as well as to the battery. As a result, the vehicle battery could serve as a backup power supply for the home in case of a power outage or to ensure power quality. R&D is needed to design, test, and commercialize the technologies needed to support the use of PHEVs for this purpose.

Mobile Distributed Generation and Link to Renewables

Integrating at-home charging systems with residential electrical systems offer utilities intriguing new power management possibilities. Like most vehicles, PHEVs will be parked approximately around 20 of every 24 hours. While they are unused assets to the consumer when not being driven, PHEVs could provide value to the utility whenever they are plugged in. Millions of fully charged PHEVs connected to the grid can complement grid control and stability by essentially providing millions of distributed resources. Because the distance between the generator (the vehicle) and the end-use consumer (the home) is negligible, the PHEV can serve as a buffer for the power grid system to ensure reliability and power quality. The use of PHEVs to provide power management services is known as mobile distributed generation. Potential advantages of widespread mobile distributed generation include fast response to control signals (which improves frequency control), reduced wear and tear on ramping electric generators, and the potential to provide frequency response service and line overload relief. Demonstration of this potential, especially as part of an "islanded" power system, would help define this value. R&D is needed to investigate the infrastructure, life-cycle cost, operations, system control and management, and other issues surrounding the use of PHEVs for mobile distributed generation.

PHEVs also present potential synergistic benefits with renewable power generation. Night-time wind power generation can be used to recharge PHEVs overnight, and solar systems can recharge the PHEVs during the day. This increases the value of these intermittent renewable resources.

Economic Analysis and Market Transformation

The synergistic nature of PHEVs with power generation, power delivery, emissions reduction, and other aspects of the electric power industry calls for careful economic/environmental analyses. To capitalize on the potential value of PHEVs, tools to perform these complex analyses for a variety of economic conditions are needed.

PHEVs also present a market transformation issue. Consumers as well as auto makers and other parties need to be motivated to invest in the new technologies. To develop ways to incentivize this investment and communicate its benefits, research is required to understand the motivations and needs of all market segments. Because usage patterns are typically entrenched, it is likely that consumers in each segment will require additional education and information to understand the benefits and ease the transition to using electricity as a fuel.

Commercial Transportation, Mass Transit, and Construction

The technological innovations of PHEVs and BEVs are expected to migrate from passenger vehicles to the commercial trucking and mass transit industries. R&D efforts are required to ensure that the power requirements of these larger vehicles are met. PHEV technology has the potential to support the reduction of diesel engine emissions, as the system enables the engine to operate more often in a steady-state condition. A strong R&D emphasis is needed on understanding current and future diesel emissions when operating in a PHEV system. For light rail transportation, R&D is needed to modernize existing systems with new control and motor systems to enable improved energy efficiency.

Today's construction equipment is a significant source of pollution. However, such equipment requires a greater burst of energy than can be provided with current electric systems. One possible solution is the use of advanced batteries and/or supercapacitors in conjunction with hydraulic systems, in which the energy storage device provides the burst of power needed to lift hydraulics and drive equipment needs. R&D is needed to test the viability of such a solution and identify other possible alternatives that reduce pollution and improve fuel efficiency for heavy equipment.

Conclusions

The widespread adoption of EDVs is critical for achieving national goals of gaining independence from foreign oil and reducing environmental emissions. By supporting R&D to speed the technologies needed to commercialize EDVs, the power industry will provide a valuable national service while realizing an enormous opportunity to develop a new sustainable market.

Because EDVs emit far less CO_2 and other pollutants than conventional vehicles (see Figure 7-10), they are most important in the "Biting the Bullet" and "Double Whammy" scenarios. While charging the vehicles does require additional generation, the power requirements are minimal compared to other energy demands and occur generally during off-peak hours. In addition, capturing CO_2 emissions from power plants is far easier than capturing emissions from individual automobiles.

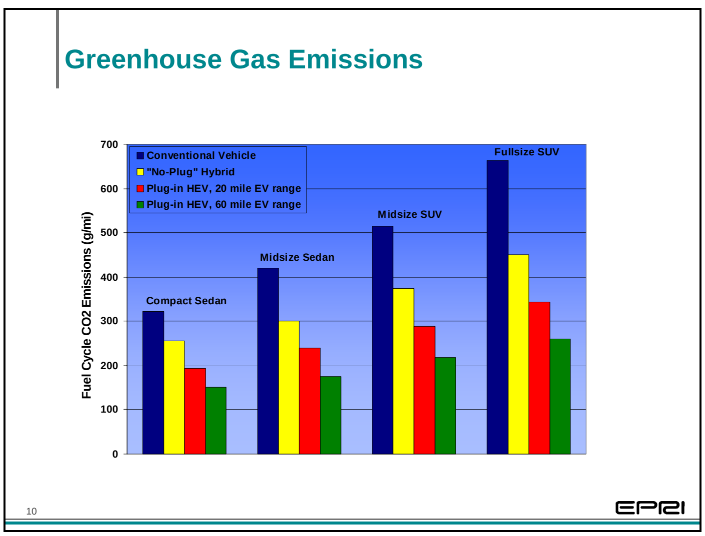

Figure 7-10
Plug-in hybrid EVs that are recharged from today's national electric grid will have 37 percent fewer greenhouse gas emissions than conventional cars and 13 percent fewer than comparable hybrids.

When natural gas prices are high, gasoline prices will probably be high as well. As a result, EDVs can be an important resource in the "Digging in Our Heels" scenario, when consumers seek relief from high prices at the pump. Similarly, when natural gas prices are low in the "Supply to the Rescue" scenario, gasoline prices will probably be low as well; this scenario also offers less environmental incentive for EDVs, as CO_2 costs are also low. However, the national value of reduced dependence on foreign oil, the economic benefits derived from investment in the U.S. rather than overseas, and the benefits of mobile distributed generation (e.g., reducing the need for power delivery system upgrades) enable PHEVs to be viable even in this scenario.

Figure 7-11 illustrates the greatest opportunities in each scenario, while Figure 7-12 illustrates the relative importance of each technology area to the scenarios. When these R&D goals are reached, the tremendous potential of EDVs can be realized by consumers, the power industry, and the nation as a whole.

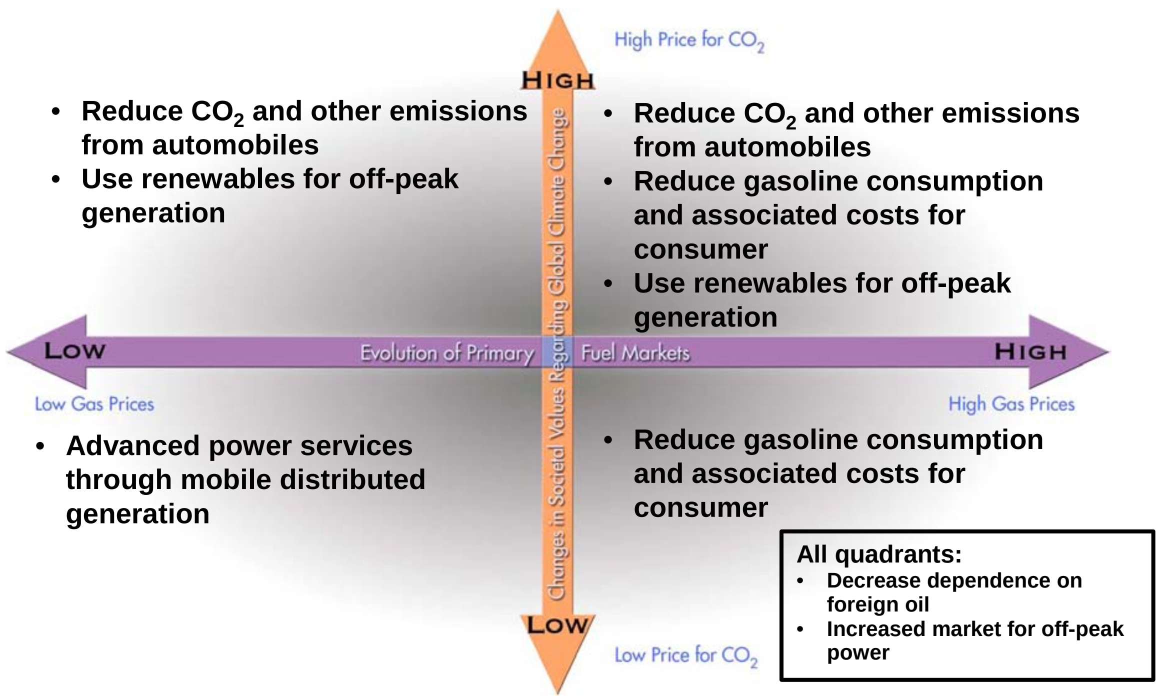

Figure 7-11
Opportunities in Each Scenario Drive Development in Electricity-based Transportation

Key R&D Topics

Following is a list of the key R&D topics for the area of electricity-based transportation:

- Develop and demonstrate low-cost plug-in hybrid vehicles in multiple on-road and off-road applications
- Document the environmental benefits of plug-in hybrid vehicles
- Develop technologies to lower advanced battery cost and improve efficiency (e.g., Li-Ion batteries)
- Evaluate vehicle integrated advanced battery, hydraulic and super-capacitor systems
- Validate advanced battery systems for electric drive applications
- Expand the knowledge base required for battery monitoring and optimization analyses
- Develop low-cost reliable vehicle controls, mechanical systems, power electronics, and charging systems
- Develop nanotechnology-enabled batteries/supercapacitors
- Conduct mobile distributed generation analysis
- Apply advances to commercial transportation, mass transit, and construction equipment

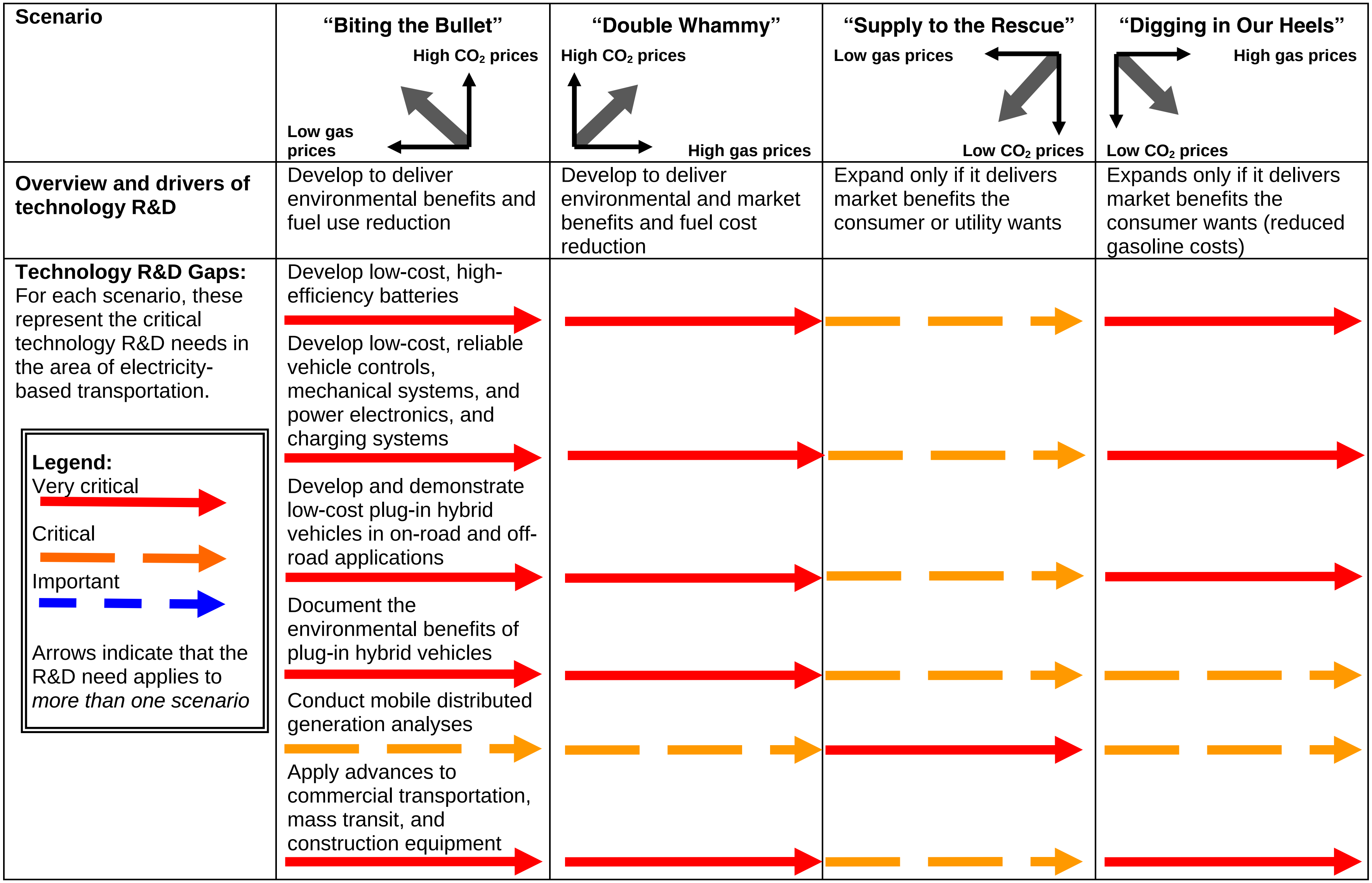

Figure 7-12
EPRI Scenario and Technology Development Matrix for Electricity-Based Transportation

8
POWER AND FUEL MARKETS

Design and improvement of power markets and assessment of fuel markets are similar in that they both rely on the principles of economics. Both markets arguably cover a wide scope. Power and fuel markets cut across a broad range of electric power industry subject areas, including aspects of power generation (market participants and fuel users), power delivery (wholesale power markets, congestion management), environment (emissions trading and incorporating externalities into markets), and end use (retail markets and retail fuel costs). While the design of a power market can determine whether it functions effectively (with billions of dollars at stake), understanding of fuel markets is crucial because fuel constitutes most of the operating cost of fossil fired power generation. Natural gas in particular has become disproportionately important to the power sector since, for many regions and in many time periods (i.e., peak prices, and in some regions and seasons, also off-peak prices), natural gas generation sets the marginal cost of power. This section focuses first on power markets, then summarizes issues related to fuels markets, and then presents R&D needs.

Power Markets Overview

The purpose of a power market system is to enhance the overall efficiency of power production and delivery. Efficiency encompasses both long-term investments and daily operations, and it includes both costs on the supply side and consumer satisfaction on the demand side. A market system, rather than central management, is used for this purpose to strengthen incentives and encourage investment. Design features are important because they affect performance by influencing the vigor of competition, the accuracy of price signals, and the degree of coordination achieved. But a market system also brings hazards that the design must eliminate: generation and transmission must be reliable and well coordinated, daily operations must be immune to gaming and abuses of market power, and financial risks must be well managed to enable the system to sustain exogenous shocks. Further, some mechanism must exist for the incentives for investment in generation and transmission that existed under the previous regulatory compact.

The stakes are high in the power market area. California clearly demonstrated that a poorly designed power market can result in increased power costs of tens of billions of dollars.

This section raises issues related to power markets but makes no assumptions about the potential future of power markets (i.e., whether the future will be dominated by market-based mechanisms, a return to regulation, or a blended/hybrid approach). This section covers key issues related to wholesale markets as well as issues related to retail markets.

Financial Risk Management and High Cost of Capital in Power Markets

Electricity is unique among commodities for two reasons. First, storing electricity in bulk is difficult and expensive using existing technologies. Instant-response storage units such as batteries, for example, have very limited capacity, while pumped hydro storage has large capacity but a long response time. Supply/demand equivalence requires very complex and long lead time infrastructure planning. Second, transporting (i.e., transmitting) electricity over very long distances is difficult.

These limitations in time and space differentiate electricity compared to other commodities and complicate financial risk management for electricity. The crucial role of financial risk management in restructured wholesale power markets was an important lesson from California. In most other industries, risk bearing is spread along the supply chain via long-term forward contracts or financial instruments for hedging. This is optimal since a seller and a buyer have common interests in mutual insurance against the volatility of spot prices. One flaw in California's legislation and regulations was to deregulate wholesale prices but to exclude utilities from using long-term contracts to hedge their default-provider obligations before retail prices were deregulated. This flaw was crucial because the utilities divested all their gas-fired generation, which could have provided a hedge against shortages in hydroelectric power, and relinquished options on gas pipeline capacity. During the four-year transitional period, the utilities were forced to purchase power at an unregulated wholesale spot market price and sell at a fixed regulated retail price. This led to huge debt (and even bankruptcy) at the utilities.

In general, none of the new legislation and regulations that enabled restructuring of power markets in the U.S. anticipated the magnitude of the financial risks participants would bear. The new financial risks in the power industry resulted from removal of risk hedges implicit in vertical integration. This risk exposure reflects a fundamental breakdown in the regulatory compact that insured utilities. This compact had compensated utilities for prudent investments and procurement costs, and also insured consumers against retail price volatility by smoothing rates over long periods. Today, utilities must cope with the financial consequences of volatile prices in wholesale markets that are largely the result of investment decisions by firms operating on the supply side.

Because of consumers' aversion to volatile retail rates, state regulators' are reluctant to allow unhindered pass-through of a utility's wholesale costs. In principle, regulators might adhere to the previous compact's reliance on capitalization and amortization of procurement costs, thus allowing pass-through via rates leveled over time. But restructuring obviates this scheme.

The result is a long-term residual risk premium on the cost of capital. Given the capital intensive nature of the electric power industry, this high cost of capital can offset the benefits of competition or restructuring. One alternative is to encourage market solutions such as imaginative financial arrangements that expand ways to provide capital to power market participants. Lessons learned in the mortgage industry may be applicable in this case; innovative financing offerings in both residential and commercial markets in recent years have dramatically expanded the options available to borrowers, while expanding the market for raising capital in this industry.

In sum, restructuring unravels the elaborate scheme of risk management that was implicit in the regulatory compact adapted to vertically integrated utilities. A research program should now define a new regulatory compact that provides an efficient allocation of risk in the industry. It should also reduce overall risk, and enable a return to the low cost of capital that was a principal advantage of the previous compact. Imaginative financial arrangement to expand ways to provide capital to market participants should also be investigated.

More specifically, sustained research is required: 1) to compare and analyze successes and failures of the various power markets established in recent years, 2) to synthesize a sequential plan for restructuring that minimizes the overall risk of systemic failures, and 3) to develop new regulatory provisions to ensure: a) planning and funding of adequate resources, and b) efficient allocation of risk in the industry, with special attention to ensuring financial solvency of default service providers. Equally important is the need to recognize the extent to which fundamental cost drivers can change, well beyond the "envelope" of scenarios adopted by companies and financial firms in the recent past. The greatest lessons have been learned from anticipating oil, natural gas, coal, sulfur dioxide (SO_2) emission allowances, and even steel prices. Yet rather than viewing the future as simply expanding uncertainty, in some instances opposite conclusions are warranted that have significant implications for risk management and technology fuel choices.

Planning and Coordination of Investments in Generation and Transmission

The transformation of the electricity industry by restructuring wholesale markets has altered fundamentally the incentives for investments in generation and transmission. In the era of vertically integrated utilities, each utility undertook long-term planning and investment for the needs of its service territory. Under this regulatory compact, shareholders of an investor-owned utility obtained a market rate of return on investments judged prudent. Because the utility was remunerated on the basis of total operations, overall efficiency of generation, transmission, and distribution was the guiding criterion. Retail consumers experienced almost none of the volatility of factor prices because costs were amortized and rates were leveled over extended time frames.

The power industry is now in jeopardy of reversion to "boom and bust" cycles resulting from uncoordinated investments undertaken myopically to exploit opportunities as they arise, and electricity needs as they become critical. During the initial years of restructuring, a disincentive to invest in new generation was attributable in part to uncertainty about the new regulatory and market regime. Fundamentally, the deficiency of investment reflects an absence of mechanisms for planning and coordination.

Unlike many countries, the U.S. has no viable national system for coordinating investments in fuels, generation, transmission, and related factors essential to the infrastructure of energy industries. In states that have restructured their wholesale power markets, state regulation of utilities is now replaced entirely by the Federal Energy Regulatory Commission (FERC) regarding all aspects of wholesale markets; state regulation remains relevant, though weakly, only for intra-state distribution and retail operations. In turn, FERC has delegated all operational aspects to independent system operators (ISOs), and regional transmission organizations (RTOs). These organizations administer tariffs regulating the daily operations of wholesale markets and grid management, but they do not own transmission or generation assets, and in most cases they cannot take financial positions in the markets they administer. Federal and state regulatory agencies stand ready to approve or disapprove proposed investments in transmission, and have some authority to thwart generation investments, in both cases largely via siting and environmental controls. But in the new era, the presumption is that investment proposals must be initiated by private parties motivated by prospective profits from returns obtained in deregulated markets. Boom and bust cycles could become prevalent if basic investments depend on occasional stimuli for new capacity each time resources become scarce.

A research program is required to 1) improve the efficiency of the many *ad hoc* schemes on which ISOs rely to manage the grid and ensure resource adequacy and 2) develop novel mechanisms to achieve coordination and overall efficiency of investments in transmission and generation. Stepping back from these modest goals, there is also a need to simply and systematically answer the question: "Is there a problem?" Lacking any "air traffic controller" in the electric power industry, a continuing need is to conduct systematic assessments of resource adequacy (i.e., capacity additions, retirements, load growth) and major uncertainties in these same fundamental factors. Such assessments should include consequences of extremes in weather. The current structure for making such assessments involves self-assessment with limited consistency. A key result, obtained in several illustrative EPRI analyses over the last few years, is a range of "reserve margin trajectories," each of which is a scenario of the supply-demand balance of capacity over the intermediate term. Beyond the value of systematic uncertainty assessment is the opportunity for a dialogue between planners and grid operators that such assessments can foster. Moreover, assessments must be revisited quite frequently due to the rapidity with which expectations for demand, for example, have been found to change.

Figure 8-1 underscores how rapidly and dramatically expectations may fluctuate in some regions; that growth is systematically exceeding expectations in some regions; and that changes have been and remain modest in some other regions. These examples underscore the need to frequently reexamine fundamental requirements in a systematic and open fashion.

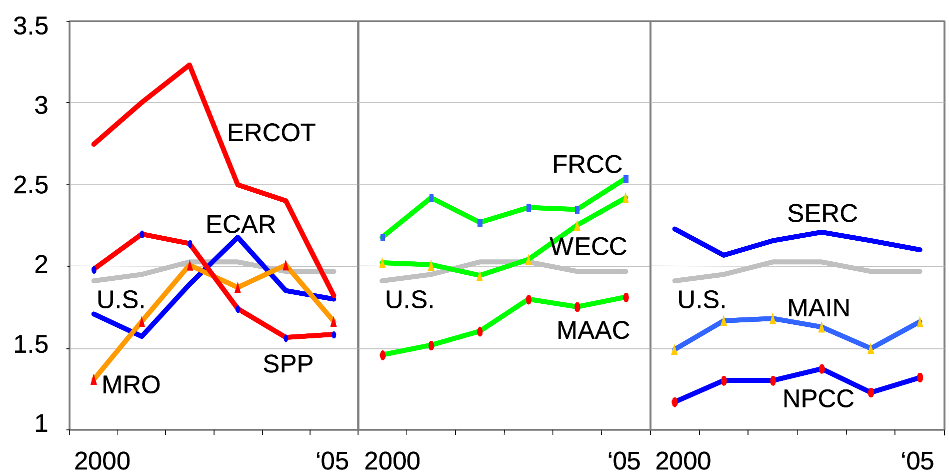

Figure 8-1
Changes in Average Annual Growth Rates for Different NERC Regions, 2000-05
Source: Assessment of power industry infrastructure, forthcoming 2006 EPRI report, 1010249.

Centralized Versus Decentralized Power Market Design

The relative merits of two fundamentally different types of market design remain a contentious issue. In the Eastern U.S., the ISOs developed from power pools (a centralized wholesale market design) and continue their previous practice of assigning the ISO responsibility for unit commitment, scheduling, and dispatch within a day-ahead time frame. California's initial "decentralized" design confined the ISO to grid management, allowing involvement in energy markets only for real-time balancing, day-ahead auctions for procuring reserves, and schedule adjustments to alleviate congestion. In California, the system suffered from severe under-scheduling by utilities, requiring massive energy purchases in real-time. In 2002, California adopted the Eastern model, making the ISO the manager of markets for energy, reserves, and transmission on a day-ahead time frame. This fits FERC's Standard Market Design but it is the opposite of developments elsewhere, especially NordPool and the United Kingdom, which separate transmission management from energy markets and resource scheduling.

The problems in California are often attributed to deficiencies of the market design. But does this mean that the power pool is the most reliable or most efficient design? Various countries have adopted decentralized designs that function well, and in the U.S. the ERCOT system in Texas is substantially decentralized.

R&D is needed to 1) analyze the strengths and weaknesses of decentralized systems, and 2) develop new designs that remedy deficiencies and provide greater efficiency and reliability.

Mitigating Market Power to Assure Generation Adequacy

The initial premise of restructuring that market incentives would contribute to efficiency is now replaced by recognition that an ISO must cope with market power and an endless variety of gaming strategies used in the real world wholesale market. Made famous by the high profile Enron scandal, the abuse of market power in a power market is an important area that requires additional research.

When specific generating units are located on the network where they are critically important to reliability, without some sort of appropriate measures, these units could exercise market power in that local area. For example, a strategically located generating unit that is sorely needed on a high load day could price its electricity at very high rates, and the ISO would need to pay the high price to maintain reliability. In fact, ISOs with large first-contingencies often pay exorbitant prices for reserve capacity from fast-start hydro and combustion turbine peaking units.

Measures are also needed in power markets to reduce the likelihood of any single utility exerting excessive horizontal market power over the market. In California, for example, the two largest investor-owned utilities were asked to divest themselves of at least one-half of their fossil-fueled generating capacity in the state.

Some ISOs have countered the market power of suppliers in those metropolitan areas requiring voltage support and local reserves by imposing reliability-must-run contracts with cost-based remuneration. Several ISOs curtail exports when reserve margins are low. Scheduled outages for maintenance now require coordination and approvals from the ISO. Various ISOs assess punitive charges on deviations from schedules, and onerous congestion prices for transmission requests not accompanied by adjustments sufficient to eliminate congestion. FERC's Standard Market Design provides the ISO with essentially complete dispatch control in real-time for units not committed to bilateral contracts. Most far-reaching are available-capacity requirements that require each load-serving entity to contract for sufficient capacity to cover its peak load plus reserve margin. All these are examples of measures adopted by ISOs to recapture some of the tight control enjoyed by vertically integrated utilities.

The process of observing the practices of market participants in this area is traditionally called market monitoring. A related area is the process of assuring that the expected benefits of power markets to various stakeholders are being realized. For example, some economic groups (e.g., middleclass, low-income consumers, etc.) may not be benefiting, while others receive disproportionate benefits. The process of market monitoring could be broadened to encompass this important function as well.

R&D is required to determine whether *ad hoc* measures to tighten control and mitigate market power are most effective for reliable operations. A systematic approach to rules and incentives, both sticks and carrots, must ensure that reliability is strengthened. Also, a broadened scope of market monitoring to include evaluation of the effectiveness of the market should be investigated.

Power Market Simulation and Modeling

Power market design requires coordinated analyses, incorporating basic economic and technical principles, as well as local, historical conditions specific to each region. But the crafting of California's legislation (AB 1890) and the design of its power market, for example, was more of a political process than a process of analyzing wholesale market design experiences in other regions or countries. A series of committees that included representatives from various special interest groups essentially assembled California's power market. The committees made compromises to satisfy all stakeholders, rather than design a system that posed the greatest chance for success in recognition of the important realities. Pressure from powerful entities in the state rushed the process, precluding careful assessment of market design and prudent planning with phased implementation. Various combinations of features from various power markets were assembled into a complicated power market model that had not been tested before full implementation.

This process in California exemplifies that fact that power market designs or design changes have been typically implemented in the field, with little or no empirical testing of how they will affect market conditions. Contributing to this problem is slow feedback as to the effectiveness (or lack thereof) of specific market rule changes. To test the viability of various power market design options before they are put into practice and to account for market contingencies in system operations, power market simulation software is needed to help all parties involved in setting up and regulating power markets (see Figure 8-2). Power market simulation software can help RTOs, regulators, and other parties involved in the design of power markets test how their markets will react to various regulatory and operational changes prior to implementing these changes in the real world. Specifically, a market simulator helps provide critical insights on alternatives for congestion management, tariff administration, system planning, and interregional coordination.

R&D is needed to build on early success in power market simulation and modeling. These models can perform the following tasks:

- Stress-test market designs under controlled laboratory conditions prior to implementation
- Design and test bidding strategies from the perspectives of various market participants
- Ensure resource adequacy by investigating how reserve margins and forward contracts can best be used to ensure sufficient resources and reliability
- Manage market power by illuminating the conditions under which markets do not behave competitively, and determining how to avoid or mitigate these conditions
- Devise and investigate ways to define and measure effective market performance via metrics, and study how various performance measures are related under different market and system conditions.

Well-specified market analysis is needed not just at the corporate level (e.g., for a power plant examining the payoff and risk associated with specific investments or capacity additions in its region). It is also important at a broader social scale, such as that pioneered by EPRI in its evaluations of the value of coal generation and coal R&D. The movement and application of commercial simulation tools initially developed for private decision support to the realm of public policy planning in the electric sector can be quite readily accomplished, as it requires a will to proceed, not a long timetable of technology development.

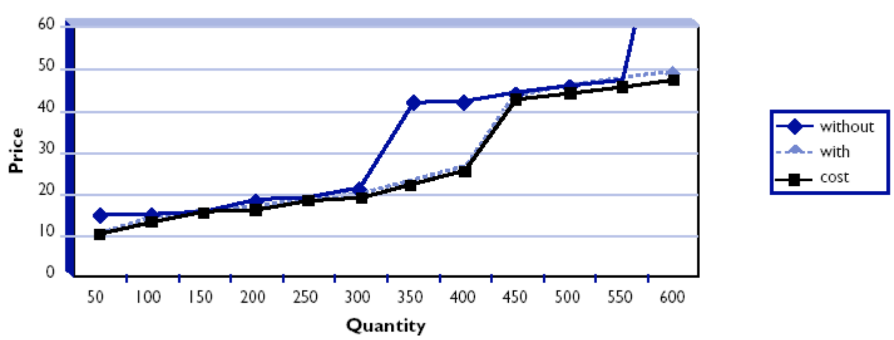

Figure 8-2
Market simulation software could, for example, predict the effects of a demand bidding program on the price of electricity, given a set of market parameters.

In this example, the model predicts that load curtailment resulting from the demand bidding program would keep the electricity price in line with the cost to produce the electricity. Conversely, if a demand bidding program was not in place, the model predicts that the electricity price would increase significantly higher that the electricity cost in some cases.

Transforming Retail Markets

Restructured wholesale markets transform a utility's role at the *retail* level. Most fundamental is that the regulatory compact's "obligation to serve" of the previous era is becoming an obligation to serve *at a price*. Regulators may require that a minimal service contract is offered as a default option, especially for residences. However, load serving entities (LSEs) offer terms of service to commercial and industrial consumers that are differentiated by quality and price. Quality has many dimensions, ranging from technical aspects of power quality to the conditions under which curtailments or interruptions can occur. Price also has many dimensions, ranging from real-time "spot" pricing to long-term contracts, and differentiation by treatment of contingencies. These include load-profiling, peak-load pricing, service curtailment at a cutoff price or according to a priority order of service, and dispatchability of a load.

It is now recognized that each consumer really buys firm power at real-time prices, but the service contract bundles this basic service with provisions that mitigate the consumer's price risk by various means for hedging or leveling financial payments. A consumer chooses among a menu of ways to control the risk of volatile spot prices it faces under the basic contract for firm service. These include financial instruments that insure against the price variability of firm power, and alternatively, they include offers of less-than-firm power at lower prices but with greater chances of curtailments, including the possibility that the consumer offers dispatchable loads in the wholesale market for reserves.

All these aspects have been known and advocated for decades, but adoption has been slow. Restructuring of wholesale markets now makes the old agenda for demand-side innovations in retail markets much more urgent.

Research is needed to devise new forms of service contracts that, when offered in a menu of options for consumers, can gain market share compared to the extremes of default minimal service and firm service at real-time prices. This should be accompanied by basic reconsideration of the regulatory policies and institutional forms that will enable the fundamental retail restructuring required. In other words, LSEs can pass through to consumers the real-time prices they pay for firm power in wholesale markets. Only when the principle is accepted that firm service pays the real-time price, and all other service plans are options offered to help the consumer mitigate price risk, will retail markets gain vigor and competition increase.

Research is also needed on a new methodology for the design of service programs, including auxiliary provisions for insurance, curtailments, and other features. This methodology must recognize that LSE retail sales is now a competitive business; a service program wins a consumer by serving the particular needs and preferences of that consumer. An LSE needs innovative financial instruments to hedge the risk it absorbs whenever it does not pass through the real-time price to a consumer. All non-financial demand-side innovations depend critically on further development of billing, metering, and real-time control devices, and as their installation becomes widespread, integration of these technological developments with the service plans designed to exploit them.

Communication With Key Power Market Stakeholders

Interactions between wholesale and retail power markets, electricity infrastructure, and market participants are becoming increasingly critical and complex. Explaining the advantages and disadvantages of various aspects of power market design is becoming more difficult. At the same time, a broad range of stakeholders – including RTOs and ISOs, utilities, decision makers in government, regulators, and the public – need to be educated and informed about power markets. While much detailed literature exists, much of it in the academic world, there is a need to concisely explain key concepts to these stakeholders at the right level of complexity and in the right form. R&D in this area can draw from lessons learned in other industries in which complex concepts must be communicated to various target audiences.

Fuel Markets: Change and Uncertainty

Critically assessing fuel markets is important because fuel prices primarily drive the economics of power production. Natural gas accounts for about 90 percent of the variable cost of operating a combustion turbine power plant, and coal accounts for about 70-85 percent of the variable cost at a coal plant. Today, fuel markets are characterized by unprecedented natural gas prices and the tremendous leverage of natural gas generation on power prices, the highest coal prices in 20 years, and unprecedented SO_2 allowance prices. These recent events and short-term consequences illustrate the complex, uncertain, and dynamic environment that decision makers face in the electric power industry. Paying the bill for fuel is a high-level industry concern that affects financing approaches and squeezes all investments in the power sector – similar in many ways to inflation, which may also be exacerbated by the same drivers, such as high oil prices. Hence, examination of the R&D needs is warranted in the area of fuel markets and their impact on power production. This area cuts across a range of fuels, including natural gas, coal, and uranium.

With respect to natural gas, the gas and power industries are more interconnected today than ever before. The 144,000-MW of gas-fired combined cycle capacity added between 1998 and 2004 is already affecting many aspects of the natural gas and power markets, and growing demand for gas by the power sector is increasing gas and power price volatility. At the same time, the fundamentals of natural gas supply have remained tight, leading to a “paradigm shift” in the gas supply outlook and to new challenges associated with Arctic and overseas sources.

Significant attention is now focusing on liquefied natural gas (LNG) projects. In addition to siting concerns (not in my backyard), critical LNG issues include integrating these projects into local markets, understanding how they may affect regional prices, and structuring commitments to secure investments in supply, transport, and regasification. (Complexities regarding burning LNG along with other sources of natural gas are covered in the section on natural gas fired power generation.)

Meanwhile, coal power, which has long been seen as a cost-effective “counterweight” to gas in the nation’s power portfolio, is also facing new challenges as average inventories fall to unprecedented low levels and reliable transportation becomes ever more vital. At the same time, many shippers are facing dramatic hikes in rail rates. New, more stringent SO_2 limits mean the industry is experiencing a new wave of capital investment in environmental control technologies (over 70 GW is indicated). Further considerations are mercury and potential carbon dioxide (CO_2) control regulations; state clean air initiatives; the expansion of renewable capacity into the energy mix; and progressive changes to the nation's power grid.

At the same time, 2005 was the second year of breakaway fuel and SO_2 allowance prices. The principal questions facing planners about the 2005-2006 spike of SO_2 emission allowance prices is why the spike occurred, and future implications for price risk. SO_2 prices affect power generation technology choice, and even fuel choice (e.g., type of coal).

Even uranium prices have tripled in the last 2-3 years. Here, the critical issue is not price (because the price of uranium is irrelevant to the price of nuclear generation), but supply assurance.

Conclusions

Price Volatility in Power Markets. Wholesale and retail price volatility is a key aspect of any examination of power market design. One important contributor to price volatility is environmental factors, chiefly the costs of various emission allowances for SO_2, nitrogen oxides (NO_x), and perhaps eventually carbon dioxide, methane, and volatile organic compounds. The experience in California in 2000-2001 illustrated the large risk factors involved: the shortage of hydroelectric imports led to greater reliance on natural gas-fueled generators, which in turn led to a shortage of emission permits for NO_x and emission prices as high as 25 times normal. Various estimates attribute as much as 20 percent of the average price of power during the peak hours of 2000 to the cost of emission permits for the marginal generators relying on natural gas.

This price volatility is particularly important, especially in light of examination of the four scenarios. In the previous era of vertical integration, utilities served as buffers against financial risks. Volatile prices along the supply chain from fuels to consumers were internalized within the utility, then smoothed over time via regulators' approved rates for retail consumers and allowed returns for shareholders. Disintegration and divestments now bring risks from volatile prices at each stage from fuels to generation to distribution, as well as new price risks from unbundled charges for reserves and transmission congestion.

This means that examination of which R&D needs are most relevant to each scenario is only one type of question to ask in the area of power markets. Another important question to ask is: how will the power market design address movement *between* quadrants? In other words, the relative price of natural gas or CO_2 credits at any given time is important, but the crucial issue is the volatility in these prices that causes movement between quadrants (see Figure 8-3). This calls for overarching R&D: development of predictive models for risk management that include predictions of price levels and volatility of all elements previously internalized within utilities, and extending this risk analysis over wide regions. It also calls for an understanding of "bounding" considerations: what halts upward or downward price movement? Here, models and detailed analysis are important; analysis is needed of the economic triggers for substituting natural gas fueled combined-cycle generation for coal generation, for example, or substitution of oils ranging from distillate to residual fuel oil for natural gas generation.

This price volatility consideration supercedes rating of R&D needs in each scenario; Figure 8-4 shows that the key R&D needs in the power markets area cut across these scenarios.

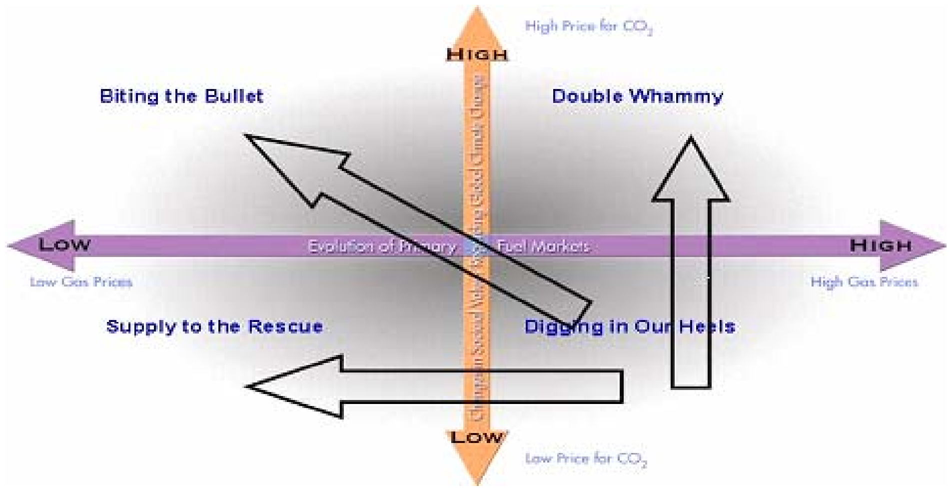

Figure 8-3
The critical factor in power and fuel markets, with regard to scenario analysis, is not only in which scenario each type of R&D should be performed, but also the critical effects when price volatility causes movement between scenarios.

Fuel Markets: R&D Needs. Overall, the dramatic and recent changes in fuel supply, emissions allowance prices (for SO_2), generation, and reserve margins/resource adequacy are reminders of the uncertainty of planning assumptions and how rapidly these assumptions can change. Conducting critical planning and making investment decisions in this environment requires a comprehensive and integrated understanding of developments in (and constraints on) energy markets, fossil generation, renewables, and nuclear generation. For most power producers, the ability to respond quickly and effectively to new market realities is a high priority.

R&D needs include ways to better understand the changing generation infrastructure and associated power, coal, emission allowance and natural gas markets; and adapt and optimize generation portfolios to meet new challenges (the generation response). To do this, R&D needs include objective and authoritative data and analyses and capabilities that provide insights into wholesale electricity markets, energy market boom-bust dynamics, gas supply risks, and price forecasting across both energy (electricity) and ancillary services (e.g., spinning and non-spinning reserves). Power producers and other stakeholders also need to better understand the forces behind skyrocketing coal and coal transportation prices, constraints on reliable delivery of coal, and implications for fuel procurement and inventory strategies, and operational planning and responses – particularly the interplay of plant budgeting, performance, and measures that increase or reduce plant operating flexibility.

R&D in this area would enable plant owners and operators to accomplish the following:

- Anticipate and develop appropriate corporate responses to escalating fuel and power costs.
- Assess the duration and "amplitude" of prices within any one scenario. Are extreme fuel prices self-correcting?
- Gain better control of the highest costs of generation and gauge the pace of retirements and capacity turnover.
- Bring industry experience to bear on development of cycling strategies, as aging units face diverse futures ranging from more intense use to less frequent use.
- Improve generation portfolio and market strategy.
- Help inform public-sector decision making.

As in the power markets area discussed earlier, addressing movement *between* scenarios is crucial (see Figure 8-3).

Key R&D Topics

Following is a list of the key R&D topics for the area of power and fuel markets:

- Develop mechanisms for efficient, coordinated investments in generation and transmission
- Assess and improve measures to detect and mitigate market manipulation
- Develop utility industry restructuring plan that addresses need to manage financial risk
- Develop innovative ways to minimize cost of capital for market participants by creation of new financial arrangements
- Analyze and remedy deficiencies in decentralized market systems (compared to centralized pools)
- Develop advanced market simulation and modeling tools, including power, fuel and emission price volatility analyses, and emission trading analysis
- Develop a decision-support framework for technology investment, capacity planning, unit retirements and mothballing, and greenhouse gas emissions reduction
- Devise new forms of service contracts and method to design new service programs for retail markets
- Gather data and conduct economic analyses to support cost effective decision making for fuels markets

Scenario	"Biting the Bullet" High CO_2 prices, Low gas prices	"Double Whammy" High CO_2 prices, High gas prices	"Supply to the Rescue" Low gas prices, Low CO_2 prices	"Digging in Our Heels" High gas prices, Low CO_2 prices
Overview and drivers of technology R&D	Power and fuel markets R&D needs apply across all scenarios; the critical issue is that price volatility requires examination of impact of movement *between* scenarios			
Technology R&D Gaps: For each scenario, these represent the critical technology R&D needs in the area of power and fuel markets. **Legend:** Very critical Critical Important Arrows indicate that the R&D need applies to *more than one scenario*	Develop restructuring plan that addresses need to manage financial risk Develop innovative ways to minimize cost of capital for market participants by creation of new financial arrangements Develop mechanisms for efficient, coordinated investments in generation and transmission Analyze and remedy deficiencies in decentralized market systems (compared to centralized pools) Assess and improve measures to mitigate market power Broaden market monitoring to include market effectiveness evaluation Advance market simulation and modeling tools For retail markets, devise new forms of service contracts and way to design new service programs Improved communication of market concepts For fuels markets, gather data & conduct ongoing economic analyses to inform decision making			

Figure 8-4
EPRI Scenario and Technology Development Matrix for Power and Fuel Markets

9
TECHNOLOGY INNOVATION/EMERGING TECHNOLOGIES

Overview

Over the years, the course of science and technology has been periodically galvanized by the emergence of innovations so fertile, robust, and far-reaching that they have changed the very course for societal developments and the quality of life. In modern times, the most important of these innovations has undoubtedly been electrification, which has not only come to drive modern industry, business, and quality of life, but in many ways has become the engine of innovation itself. Other key technology research areas of the past century – mass production, communications, aircraft technology, polymer chemistry, material science, environmental science, and computer science – have also changed our lives in fundamental ways. What they have in common is their ability to break long-standing limits of efficiency and capability and spur the overall reach and tempo of progress in the U.S. and around the world.

Finding, developing, and mining these key innovative technologies involves a somewhat different approach than for R&D focused on incremental improvements. Research focused on innovation tends to be highly exploratory and broad in its potential applications. This means that R&D in the innovation arena is wide-ranging and research horizons are longer. The resulting technology advances are cross-cutting, both in the technical disciplines involved in their exploration, and in the further lines of investigation they are likely to seed. There is an expectation that some avenues of investigation will not pan out, but the limit-breaking innovations that are successfully developed have the potential for huge payoffs. Thus, the research risk in this type of R&D is higher than R&D focused on incremental improvements in hardware or software. Fortunately, past history of technology R&D in high risk areas has shown convincingly that little is wasted in the pursuit of innovation; even apparent failures have a way of uncovering information and ideas that have real value in the final analysis.

While it is difficult to divine the future of any research endeavor focused on innovation, it is especially hard to foresee the result and value of the more cutting-edge technology R&D. Early computer scientists asked in the 1950s what they were working on, said “a machine for making numerical calculations much more quickly.” There was absolutely no idea that, decades later, computers would constitute a technology with a central role in nearly every aspect of our lives, from manufacturing and commerce to communications, transportation, and entertainment. As a result, the focus of research on innovative technologies is changing constantly and tends to follow the paths of unexpected discoveries and breakthroughs as they occur.

This section focuses on six "innovation" technology areas that appear to have a rich potential for dramatic improvements and applications in the electric power industry:

- Biotechnology and biomimesis
- Smart materials
- Nanotechnology
- Information technology
- Sensors
- The hydrogen-electric economy

These six technology platform areas have been selected on the basis of past efforts in the *Electricity Technology Roadmap* to identify key underlying technologies. The emphasis is primarily on long-term, limit-breaking developments. Higher-temperature alloys for turbines and steam generator components, for example, are certainly important, but their development is likely to follow from conventional, near-term refinement work and is not addressed here; on the other hand, more-innovative solutions to higher temperature and/or higher pressure turbine problems – and much larger improvements – may result from long-term research on biomimetic ceramics or fullerene composite materials.

The remainder of this section summarizes the outlook and future possibilities for these six enabling technology areas.

Biotechnology

Already useful in pharmaceutical and agricultural applications, biotechnology has the potential to provide environmentally-sound, energy efficient improvements to a variety of electric utility applications. Some of these applications include bioremediation and phytoremediation of wastes, increasing the production of biomass, genetically enhancing enzymes for industrial process improvements, production of hydrogen, carbon capture, and corrosion inhibition.

Work on environmental biotechnology, such as the development of microorganisms (bioremediation) and plants (phytoremediation) that can process and destroy toxic chemicals such as zinc, arsenic, cadmium or selenium, is proving valuable. EPRI-sponsored work on phytoremediation has investigated the use of genetically engineered mustard plants for removing selenium and heavy metals. Another project examined various wetland plants to identify which of the plants would be most effective at removing trace elements such as Pb, As, Se, Cd, and Cr from utility wastewater. Future research should focus on genetically enhancing promising plant species to increase their waste removal ability and to create a positive public perception that genetically modified plants are environmentally beneficial.

Biotechnology can increase the efficient, speedy production of biomass that can be used as feedstock for electricity generation. Work is underway to genetically enhance crops, such as loblolly pine, eucalyptus, and cottonwood, to maximize the growth rate/yield of biomass. Plants such as switch grass offer the advantages of soil erosion control, CO_2 removal from the air, and production of fuel for generating electricity or as a feedstock for production of biofuels such as ethanol. Genomic research is needed to address increasing plant growth rates and feedstock trait modification by introducing traits that might otherwise be genetically intractable through traditional breeding.

Genetically enhanced enzymes can provide improved catalysts that increase industrial production of ethanol and other products while also reducing waste byproducts and reducing environmental impact. Biocatalysts can be useful in converting cellulosic feedstock into ethanol, and producing products such as plastics, chemicals, textiles, paper, and pulp. For economic reasons, biocatalytic processes are currently being developed for industrial products with costs of $20-$30/kilogram or greater. Some of these products include polymers, vitamins, and plastics. By discovering better catalysts and increasing the activity and stability of these catalysts, synthesis of products in the $5-$20/kilogram range could be feasible; and attempts to develop products in the $2-$5/kilogram range may be worth considering. Improving industrial processes helps utilities by improving the efficiency and productivity of the industrial sector, thereby increasing kWh sales to a strengthening industrial electric customer base.

Biological processes could also provide efficient, environmentally-friendly means of producing hydrogen. As discussed later in this section, developing a hydrogen-electric economy could yield substantial economic and environmental benefits to society and utilities. Potential biotechnology-enhanced processes for producing hydrogen could employ the following: light-induced photosynthetic electron transport/decomposition of water, hydrogenase enzymes to transfer electrons from photolysis reactions with algae and cyanobacteria, and byproducts of nitrogen fixation. Research needed would include the development of enzymes with the desired hydrogenase properties, characterization of the molecular machines/activity needed to produce hydrogen, and associated metabolic engineering and modeling.

Biotechnology using mixed algae cultures and other means can remove carbon from power plant exhaust. Dominant organisms in surface waters include cyanobacteria that capture CO_2 and light to carry out photosynthesis. If the activity of these bacteria, thought to be the most abundant photosynthetic organisms on earth, could be genetically enhanced, then the sequestration of carbon could be correspondingly increased. Similar enhancements should be sought for the activity of diatoms that also live in the surface water and convert CO_2 and nutrients into hard silicates that are “stored” as ocean sediments.

Bacterial colonies that form on metal surfaces are usually damaging. However, industrial bioengineering research is showing the potential for beneficial biofilms. In EPRI-sponsored field experiments, biofilms seeded by adding naturally occurring bacteria to closed-loop side streams proved successful in reducing corrosion rates under conditions found in service water systems typically present in power generation facilities (see Figure 9-1). In laboratory testing, the concept of corrosion protection by biofilms containing *genetically-modified* bacteria that secrete corrosion-inhibiting chemicals and antimicrobial compounds was verified. Thus, this technology shows promise for corrosion control in piping and pressure vessels in steam generation facilities used for power production.

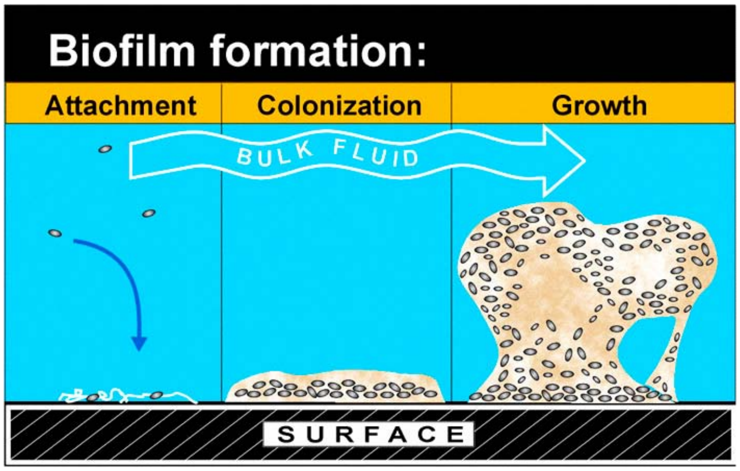

Figure 9-1
Biofilms form protective layers on power plant components, demonstrating the synthesis of advances in industrial bioengineering and the electric power industry.

Biomimetic materials – man-made substances that imitate the characteristics of natural substances or systems – are the subject of much research, as these materials often promise superior properties, functionality, and adaptability. Biomimetic materials may be used as direct substitutes for existing materials, enabling technologies for which existing materials are inadequate, or as the basis for new applications. Photovoltaic cells may be improved using light-gathering and self-assembly mechanisms suggested by plant photosynthesis. Miming the ability of some biological systems to pump protons across cellular membranes may allow the development of advanced fuel cells that operate at room temperature. Realization of these biomimetic applications will generally require research to better understand the natural processes being copied and research on how similar functions can be engineered in a man-made system.

Smart Materials

Smart materials and structures have the unique capability to sense and physically respond to changes in their environments – to changes in temperature, pH, or magnetic field, for example. Generally consisting of a sensor, an actuator, and a processor, smart materials and structures based on such materials as piezoelectric polymers, shape-memory alloys, hydrogels, and fiber optics can function autonomously in an almost biological manner. Smart materials have already appeared in a number of consumer products and are being studied extensively for aircraft, aerospace, automotive, electronics, and medical applications.

In the electric power generation field, smart materials and structures hold promise for real-time condition assessment of critical power plant components, control of power plant chemistry, and control of undesirable combustion products. In the transmission and distribution area, smart materials and structures could be used to avoid subsynchronous resonance between the generator and the interconnected grid, and adjust transmission line loads to account for real-time thermal conditions.

Smart materials include the following candidates that can be used as actuators and sensors:

- Piezoelectric ceramics and polymers
- Shape memory alloys or polymers
- Conductive polymers that change shape when exposed to an electric field
- Rheological fluids that stiffen when exposed to an electric field
- Magnetorestrictive materials that change dimensions when exposed to a magnetic field
- Polymeric biomaterials such as polypeptides, that contract and expand in response to temperature or chemical changes in their environment
- Hydrogels that change shape in response to electric fields, light, electromagnetic radiation, temperature, or pH
- Fiber optics that signal environmental change through analysis of light transmitted through them.

Real-time condition assessment of critical power plant components can provide early warning of structural impairment that could cause an unplanned forced outage. Stress-corrosion cracking, corrosion fatigue, creep, and creep fatigue are difficult to detect by traditional means. Smart materials and sensors (e.g., fiber optics, microsensors, chemical sensors, and corrosion detectors) could provide data that should help avoid costly overdesign of components, conservatism and premature servicing, and replacement that is currently needed to minimize unplanned power plant outages.

Control of power plant cycle chemistry could be accomplished rapidly and automatically with smart systems to inject chemicals that counter pollutants or chemical imbalances. The penalties for exceeding well-established limits on contaminants can be severe, including boiler tube failures, localized severe corrosion, cracked steam-turbine disks and blades, and increased erosion of turbine components by oxide particles spalled from steam-touched tubes and pipes. Any of these ills can cause forced outages of substantial duration. To prevent these occurrences, dissolved oxygen, chloride ions, and a host of other impurities must be controlled at a parts-per-billion level. This is a formidable challenge, considering that a large steam generator circulates millions of gallons of water and steam per hour. There is a clear need for smart systems to address this challenge: distributed on-line chemical sensors capable of functioning in high-temperature water and steam, chemical injectors to counter pollutants or chemical imbalances, and processors to coordinate multifunctional sensors and actuators.

Control of undesirable combustion products such as nitrogen oxides (NO_x) created in boilers could be accomplished by adjusting the combustion process with sensor and activation devices distributed at different boiler locations. The primary approach to reducing NO_x is to delay combustion, thereby lowering the “hot spot” combustion temperature. This is generally done by reducing excess oxygen levels in the boiler, which reduces NO_x formation by limiting the amount of oxygen available to fuel-bound nitrogen. An alternative approach is the use of low-NO_x burner systems, which carefully control the introduction of fuel and air into the burner to create a fuel-rich core that causes the temperature of the remaining combustibles to decrease below the temperature at which NO_x is produced – around 1540°C/2800°F. An ideal system of smart materials and sensors, processors, and actuators could make either of these strategies possible by analyzing fuel as it enters a combustor, changing the combustion conditions in real time to minimize pollutant formation, and selectively activating control devices that extract residual pollutants from the stack gas.

Smart materials could also be used to avoid potentially catastrophic subsynchronous resonance in generating units that results when the natural frequency of the generator matches the resonant electric frequency of the interconnected power grid. A smart system with the ability to measure subsynchronous resonance and an intelligent processor to analyze signals and coordinate appropriate actuation of switchable filters and series capacitors in real time would avoid the costly simulations and systems detuning that are currently employed to avoid the problem.

One of the primary power transmission constraints is the thermal capacity of the conductor in high voltage transmission lines. High temperatures degrade the strength of the line, causing sag that precipitates line faults. Thermal operating limits are traditionally established using simulations that provide conservative thermal predictions based on electrical and thermal/environmental parameters. If operating limits were based on the measurements of the actual thermal condition of the transmission line using smart fiber-optic sensors, perhaps 5-15 percent more power could be safely transmitted over the line. This utility application has the potential to be much less expensive and more reliable than existing line sag monitoring systems.

Critical capability gaps relate to integrating smart materials into sensors, conductors, actuators, and processors; embedding the smart components into the structure to be controlled; and facilitating communication between smart structure components and the external world. These functions will draw heavily on advances in nanotechnology, sensors, and information technology described in other sections in this section.

Nanotechnology

The miniaturization push, led primarily by the makers of integrated circuits, is now being ratcheted from the micro-scale to the nano-scale, a size a thousand times smaller. Nanotechnology operates on the level of individual molecules and atoms – the basic building blocks of matter. By learning how to handle and assemble these blocks appropriately, researchers hope to develop specialized materials and customized functional devices unlike any that presently exist.

Nanotechnology is rapidly evolving across a range of scientific and engineering disciplines. It offers the potential to improve the economic and environmental performance, reliability, and security of the existing electricity infrastructure. It also represents an enabling science and technology area for electricity-based innovations – including disruptive technologies – that may create substantial opportunities and challenges for the electric power industry. These opportunities appear most likely to be in photovoltaics, thermoelectrics, sensors, fullerenes/structural materials, fuel cells, and solid state lighting.

Nanotechnology-enabled devices could offer cost-performance improvements over existing photovoltaic materials platforms. A primary focus will be lowering costs by a factor of ten from current levels of around $300/m^2 to make this technology competitive. Nanotechnology approaches that explore surface/interface phenomena should permit the use of semiconductors in the interior that have modest performance characteristics and can be produced with inexpensive solution-based methods rather than via high-vacuum methods.

Nanotechnology offers the potential to yield thermoelectric materials with attractive properties for electricity-based cooling systems. The performance of these devices may be enhanced by modulating their composition at the nanoscale. Thermoelectric devices have potential application as topping cycles for electricity generation, as well as for temperature control of otherwise difficult-to-cool equipment such as high performance chips and electronic equipment.

Embedded nanotechnology-enabled sensors are an extremely promising candidate for use in intelligent, interactive, self-diagnosing, and self-healing components and systems. Other potential applications are nanosensors for detecting combustion products such as NO_x or ammonia (NH_3) in high temperature streams; pH measurement in circulating water to prevent corrosion; distributed sensing of voltage and current in generators, transformers and power lines; and analysis of partial discharge fault gases dissolved in transformer oil.

Carbon nanotubes and “fullerenes” offer the potential of extremely high strength structural materials in many applications ranging from structural beams, struts, and cables to rotating machinery. Electrical applications range from highly conductive (and perhaps superconductive) wires and cables to electron emitters in flat panel displays and magnetic recording media for data storage. Because nanotubes are incredibly thin and have such versatile electrical properties, they are ideal building blocks for nanoscale electronic devices, which can be used for product applications at the power plant, on transmission and distribution systems, and at the end-use scale. Other potential applications of nanotechnology structural materials include overhead transmission cables and flywheels for energy storage systems. Initially, carbon nanotubes will likely need to be combined with metals or polymers to provide acceptable ductility and manufacturability. Eventually, it may be possible to develop overhead conductors and flywheels out of pure nanostructures that have acceptable ductility and malleability.

Nanotechnology promises to improve the membranes used in solid oxide fuel cells for stationary power generation. Nanoparticles that sinter at temperatures significantly lower than conventional powders offer promise in constructing solid oxide fuel cells. In addition, nanostructured electrodes and nanograined solid oxide electrolytes may improve performance by enhancing electrochemical reactions and ionic conduction.

Improved light emitting diodes and solid-state lighting have the potential of achieving efficiencies of greater than 50 percent, replacing incandescent lamps with efficiencies of approximately 8 percent and fluorescent lamps with efficiencies of up to 25 percent. Nanotechnology could improve substrates, reducing defects by a factor of 100, enhance microcavity effects for better light extraction, and create quantum dots to be used as phosphors.

Strategic investments have supported proof-of-concept studies and developmental work on industry nanotechnology applications with significant near-term potential. Over the next 20 years, these technology investments could lead to promising uses of nanotechnology in electricity generation, storage, delivery, and end-use systems.

Information Technology

Information technology (IT) – hardware and software that enable the effective collection and processing of data – has been a cornerstone of efficiency and business productivity for the last decade. Led by the computer, semiconductor, and telecommunications industries, IT has brought incredible improvements in the speed and effectiveness of communications, computations, transactions, and record keeping. Trends in business and personal technology – expanded interconnection, distributed systems, and automated control, for example – will place significant new demands on IT capabilities in future systems, especially the nation's electric power infrastructure. Advances in IT in the areas of controlling dynamic processes, data mining, man-machine interfaces, and information security and privacy will help improve electric utility operations in a number of important areas. These include expanded, more complex interconnections and distributed systems, handling of massive amounts of customer and operating data, automatic control of complex networks, control-room operations, and handling of critical, secure information.

Monitoring and control of a complex dynamic infrastructure system like the electricity grid is a major challenge. The multi-layered grid is vulnerable to many different types of disturbances. While strong centralized control is essential to reliable operations, this requires multiple, high data-rate, two-way communication links, a powerful central computing facility, and an elaborate operations control center, all of which are especially vulnerable when they are needed most – during serious system stresses or power disruptions. For deeper protection, intelligent distributed control is also required, which would enable parts of the network to remain operational and even automatically enable reconfiguration in the event of local failures or threats of failure. Distributed control capability is becoming available in next-generation integrated sensors that are equipped with two-way communication capability and support "intelligent agent" functions – not just sensing, but data assessment, adaptive learning, decision making, and actuation as well. The development of Intelligent Electronic Devices that combine sensors, telecommunication units, computers, and actuators will allow highly automated adjustments to be made at many points on the system and protect substantially against cascading failures. The use of distributed intelligent agents also opens the door to the development of a self-healing power grid that responds adaptively to counteract disturbances at the site of their occurrence.

The proliferation of computers, communication networks, terminals, and sensing devices has made data collection an effortless task. However, the captured data is useless unless it is converted into information, and knowledge is developed to use it effectively. In response to this opportunity, a variety of commercial computer-based products are now available to perform data mining or, in a slightly broader context, knowledge discovery. Data mining offers opportunities to take practical advantage of data that businesses and organizations have been collecting and archiving for years. For example, data mining analysis of consumer purchases is now widely used to detect buying patterns, adjust inventories, assess the effectiveness of advertising campaigns, and optimize pricing strategies. And the fraud division of a credit card company is likely to contact a consumer if unusual activity or a suspicious pattern is detected in the use of a credit card.

Similar data mining opportunities could exist for power companies, such as the analysis of customer energy use to create attractive service packages or the analysis of weather data to predict next-day electricity demand during peak seasons. But the most valuable applications are likely to relate to operation of the power system itself, making use of the growing number of sensors connected to generation equipment and the power delivery grid. In addition to the electrical disturbance and contingency analyses mentioned earlier, data mining can be used to uncover recurring sensor patterns that signal imminent failure of components, permitting their repair or replacement before destructive failure occurs. Such pattern recognition is at the heart of the data mining process, and a number of techniques are used to accomplish it. Statistical analysis, the earliest method of detecting data trends, has been largely overshadowed by a number of techniques that have been placed under the general label of artificial intelligence: cluster analysis, neural networks, fuzzy logic, or rough sets. Each has strengths that are appropriate to particular situations. For example, tree-based machine learning allows a complex problem to be handled as a series of simpler problems. Fuzzy logic and rough sets permit accommodation of vagueness and imprecision in the data. Neural networks are effective for adaptive learning and the modeling of nonlinear dynamic systems. In practice, these techniques are combined synergistically to obtain the best result. For example, neural networks, machine learning, and fuzzy systems work together well in extracting knowledge from complex networks.

IT plays a key role in the optimization of man-machine interfaces and other human factors issues. Basically, the problem is finding the most effective way for machines and humans to work together, and the data glut is again largely at the center of the problem. Much of the answer is simply a matter of how information is packaged for viewing. The operational state of the electric power grid at any particular moment is so complicated and involves so many changing variables that the design of effective control center interfaces has become a particularly difficult challenge. Improved displays are making use of such advances as parallel coordinate transformation – an innovative graphical presentation – to display very high-dimensional data in a way that can be rapidly assimilated by power plant or power system operators. IT innovations are also expected to have applications in personnel training and optimization of human performance. Virtual reality may be particularly useful in training for maintenance or rapid repair work, especially those involving hazardous situations. Voice recognition is another technology expected to come into broad use over the next decade; replacement of keyboarding with voice-based input capability could greatly streamline and simplify human interaction with computers and other electronic control equipment.

An increasingly important topic for all IT is security and/or privacy of information. As competition increases with the deregulation and restructuring of the electric power industry, information security will become much more important than in the past. In addition, the possibility of terrorism (via cyber attack) has become a real threat. Since electricity is clearly the most important infrastructure need for the effective operation of a country's business, communication, and emergency response, the nation's electric power supply structure is a credible target for terrorist attack. The need for security poses particular difficulties for the power industry, which exists as a highly distributed network of individual power companies that cooperate to provide increased reliability over wide areas. Key operational systems depend on real-time internal and external communication links. The functional diversity of the individual companies involved has resulted in design of these systems with open communication protocols that are user-configurable and often based on telecommunication technologies. Even control systems that were originally designed for use with proprietary, stand-alone communication networks are often later connected to the Internet because of its productivity advantages and lower costs. Development of highly reliable, secure control and information management systems for these networks is paramount.

The increased use of electronic automation also identifies the need to provide data security in the power infrastructure's operational systems. For example, reduced personnel at remote sites make these sites more vulnerable to hostile threats. Interconnection of automation and control systems with public data networks makes them accessible to individuals and organizations from any worldwide location using an inexpensive computer and a modem. And the use of networked electronic systems for metering, scheduling, trading, or e-commerce imposes numerous risks of financial manipulation and fraud. Other IT applications involve improvement of such human aspects as internal knowledge retention and routing, and the upgrading of information security and privacy protection.

Sensors

Various industries have always been dependent on measurement instruments to ensure safe, efficient processes and operations. Today, almost every engineering system incorporates sophisticated sensor technology to achieve these goals. An increased focus on cost and efficiency, along with the growing complexity of industrial processes and systems, has placed new demands on measurement and monitoring technology. Operators are asking for more accurate data on more variables from more system locations in real time. The push for "perfect intelligence" and instantaneous response makes advanced sensors a key technology platform for the future of industry and especially for the power industry's goals of enhanced power quality, service reliability, and system integration. Overcoming today's limitations on temperature, robustness, versatility, and size will facilitate achievement of a number of long-standing power system goals, including real-time characterization of plant emissions and waste streams, distributed measurement of transformer winding temperatures, and online monitoring of pH in steam plant circulation water.

In recent years, advances in electronic signal processing and conditioning have resulted in improved instrumentation and controls for power plants. Many utilities have replaced analog and pneumatic controls with digital control systems in order to reduce operating costs and to increase the capability to respond to system dispatch. These digital control systems can regulate processes with less than 0.25 percent uncertainty, compared with 2-3 percent uncertainty for analog controls. However, the conventional sensors still common in power plants cannot, without frequent calibration, provide the levels of accuracy consistent with sophisticated digital control systems.

Opportunities for better measurements are numerous in every sector of the power industry. For example, a coal-fired steam plant requires about 400 sensors for measuring pressure, and many pressure sensors in typical plants still rely on fill fluids to separate process streams from the gauge mechanisms. These devices are subject to failures when fill fluids leak, and the failures are difficult to detect. In addition, all conventional pressure sensors drift with time, which necessitates disproportionately large efforts to restore accuracy and verify operability.

The power industry, with its large capital investment in expensive machinery and its complicated, extremely dynamic T&D delivery system, has an especially pressing need for advanced sensors that are small enough to be used in distributed applications throughout the power system (see Figure 9-2). Sensors that can accurately detect and measure a wide range of chemical species are needed, as are sensors and gauges robust enough to withstand the harsh temperatures and chemical environments characteristic of power plants.

Advanced fiber optic sensors – devices based on sapphire fibers or fiber Bragg gratings, for instance – are especially important because of their versatility, small size, and freedom from magnetic interference. These devices offer the potential of accurately measuring temperature and strain as well as electric and magnetic fields or chemical species. This could facilitate the sensing of chemical species in emissions and waste streams.

Optical microsensors are needed for distributed sensing of voltage and current (see the section on smart materials). This could possibly result from a combination of sensor concepts such as coating fiber Bragg grating with materials that change size or shape in electric or magnetic fields.

Distributed measurement of temperatures in transformer windings can be achieved using a number of approaches, including finding a polymer that is impervious to transformer oil; providing a distributed fiber-optic temperature sensor based on Rayleigh or Raman backscattering; and developing improved coatings for distributed fiber-optic temperature sensors.

Corrosion of steam plant boiler tubes, turbine disks, and turbine blades is determined to a large extent by the pH and electrochemical potential of the circulating water. Since the physical/chemical properties of water are highly sensitive to temperature, there is strong incentive to develop online sensors for pH that can be used at system temperatures, rather than relying on analytical extrapolations from grab samples cooled to ambient temperature, as is the typical current practice. Attempts to develop such sensors for use at elevated temperatures must overcome two problems: 1) the hot water degrades the sensor materials, and 2) interaction of the sensor with the high-purity water characteristic of cooling loops can affect the pH being measured. Research has shown that some transducer materials can function in this difficult environment, at least on the macroscale and for up to 100 hours. The feasibility of developing relatively inexpensive, microscale, “smart” sensors for measuring pH in recirculating water needs to be demonstrated.

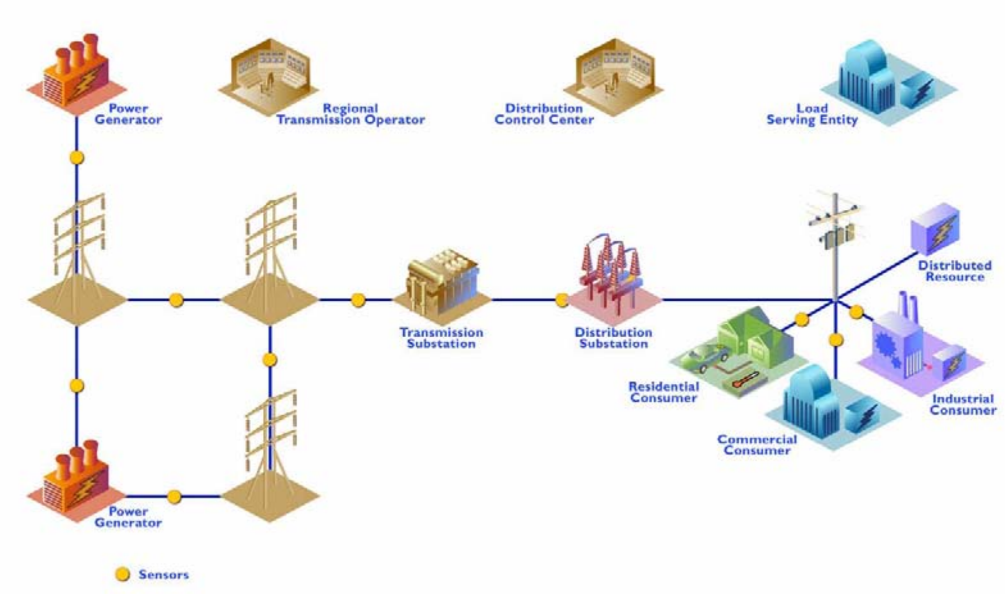

Figure 9-2
Sensors can be deployed throughout the power delivery system to enhance reliability, aid system operation, and reduce maintenance cost.

The Hydrogen-Electric Economy

Hydrogen offers the potential as an energy carrier that complements electricity and as a fuel for transportation and electricity generation. Both hydrogen and electricity are clean at the point of use. Electricity is more flexible and less costly for large scale "stationary" applications, while hydrogen has advantages as a transport fuel and a fuel for distributed fuel cell generation units. Using electricity via electrolysis to produce hydrogen also increases the capacity factor of large power plants during low load, off-peak time periods, which is desirable from an asset utilization viewpoint. Hydrogen production using biotechnology offers the potential to exercise an environmentally sound strategy that could reduce carbon dioxide (CO_2) emissions and reduce the need for foreign petroleum.

Yet, to move toward a hydrogen-electric economy, formidable technological and economic challenges must be addressed at every stage in the hydrogen energy chain – from production to transport, local delivery and storage, and end use. The cost of hydrogen production today is substantially higher than that of energy sources such as coal or natural gas. The production cost of hydrogen is driven by the cost of electrolysis, the cost of fossil feed stocks used to produce hydrogen from steam reforming of methane, and the cost for coal gasification processes. Similarly, hydrogen storage adds to the overall cost, because of the need for technologies to compress, liquefy, or convert the gas to a solid form (e.g., to metal hydrides). Also, the ultimate energy efficiency gains from the overall fuel cycle, as well as CO_2 emissions savings from the development of a hydrogen-electric economy, are uncertain.

The cleanest way to produce hydrogen is to use electricity from renewable or nuclear sources to electrolyze water into its component gases. The cost of this approach is now about four times higher than that of producing hydrogen from fossil energy sources. This indicates that near-term production of hydrogen is likely to focus on gasification of coal or steam reforming of methane, with sequestration of the CO_2 produced. This approach used in the near term will enable the development of a hydrogen infrastructure and demonstration of early hydrogen applications. At the same time, work can progress to reduce the costs of electrolysis, improve use of biotechnology to produce hydrogen (i.e., biohydrogen), and improve hydrogen storage technologies. The U.S. Department of Energy (DOE) has begun a “nuclear-hydrogen” initiative that plans to demonstrate a high-temperature gas reactor with the capability to split water using an emission-free sulfur iodine process. The high-temperature requirements of this process present engineering challenges, but the payoff, if successful, could include the large-scale production of hydrogen at a competitive price.

While the density of hydrogen use is low, hydrogen will be delivered in both gas and liquid forms, via truck, rail, barge, or on-site generation. When the intensity of use justifies the capital cost, pipelines will provide more economical long-distance hydrogen transport, as in the natural gas distribution industry. Currently, hydrogen pipelines are used in only a few areas of the U.S., but they demonstrate that the concept is feasible. (A large hydrogen pipeline has been operating in the Netherlands for over ten years.) Air product companies operate short hydrogen pipelines in several states. However, very high pressure or cryogenic hydrogen pipelines that are more than 500 miles long will present challenges in materials, construction cost, maintenance, safety, and reliable operation. R&D investment is needed in these critical areas.

If the hydrogen delivery system became an integral part of the electricity generation infrastructure, then hydrogen pipelines coordinated with fuel cells and other means of converting hydrogen into electricity could provide a valuable source of electric power. The smart grid concept discussed earlier in this section could capitalize on this approach. This system could deliver both hydrogen and electricity over long distances. Alternate delivery forms are also being developed, such as the transport of hydrogen in safe compounds or chemical forms ranging from solid metal hydrides to ammonia.

As with the hydrogen delivery infrastructure, a major obstacle on the road toward hydrogen storage is cost-effectively compressing hydrogen. To achieve an energy density comparable to gasoline, hydrogen must be pressurized to about 10,000 psi. Mechanical compression systems are available to reach this very high pressure, but are prohibitively costly and consume about 50 percent of the energy of the hydrogen being processed. Studies indicate that hydrogen can also be generated at this density via high-pressure electrolyzers or concentrator cells at about 90 percent efficiency. Although such electrolyzers have not yet been built, programs are underway to develop a high-pressure unit. Promising developments of this nature need continued R&D support.

Emerging high-pressure gas storage tank materials are lighter and better able to provide containment, typically using a protective outside layer to improve impact resistance and safety. Hydrogen can also be stored in delivery pipelines by operating the pipeline between high- and low-pressure levels.

Liquid hydrogen stored in cryogenic containers requires less volume than gas storage. However, liquefaction consumes large quantities of electric energy – equivalent to about one-third of the energy value of the input hydrogen. The cost of liquid hydrogen containment is also a major concern. Hydrogen can also be stored in a chemical compound using a variety of technologies. In reversible metal-hydride storage, metals are alloyed to optimize both the system weight and the hydrogen recovery temperature. In storage, the material undergoes a chemical reaction with another substance, such as water, that releases the hydrogen from the hydride. Both of these approaches are in early development. A further solid-state storage possibility involves the use of carbon nanotubes, but this option is only at the lab-scale verification stage. If successfully developed, it may provide the lightest, smallest, and safest method for applications such as vehicles.

Early mass-market hydrogen fuel cells may appear first either in fuel cell electric vehicles or in distributed heat and power applications; the latter is technically easier but current government R&D is focused more on automotive uses. Plug-in fuel cell vehicles may be used at rest (typically about 20 hours per day) to meet a portion of grid power requirements, and stationary fuel cells could meet much of the remaining power requirements. (For more information, refer to the section in this report on electricity-based transportation.)

Even during a transition period using fossil-derived hydrogen, fuel cells may achieve higher "well-to-wheels" efficiencies and lower total cycle emissions than internal combustion engines or most other motive power devices. More research is necessary to develop, test feasibility, and deploy practical technology, infrastructure, and high-value applications for fuel cells and other direct hydrogen uses.

Using hydrogen to generate electricity with fuel cells is an important element of the hydrogen-electric economy. Almost all of the hydrogen presently used in industrial applications is formed from natural gas in a process known as steam reforming, which produces hydrogen from methane (CH_4) and generates CO_2 that is currently vented to the atmosphere. An energy reduction of as much as 30 percent occurs when natural gas is reformed into hydrogen, and fuel cell power plants presently cost up to eight times as much to build and cannot be built today in one "module" as large as conventional power plant modules. If, for the next several generations, steam reformation of natural gas (or other hydrocarbons) remains the only economical way to manufacture hydrogen, an interim solution to manage the CO_2 generated by hydrogen production using steam reforming will be needed.

Conclusions

Innovative technologies promise a range of applications that help to solve anticipated challenges in all four scenarios (see Figure 9-3). For example, in high CO_2 price scenarios, various technologies can address the need for breakthroughs in low cost, effective renewable and storage technologies. These technologies can also help reduce emissions from power plants to help meet carbon constraints and enhance efficient use of power generation and power delivery assets.

In low CO_2 price scenarios, these technologies can help address other pressing issues that arise. For example, these technologies can help increase power delivery system capacity, enhance monitoring and control of the power system, and reduce wear in existing central station plants. These benefits support the needs to maintain the heavily loaded power delivery system and power generation assets in both “supply to the rescue” and “digging in our heels” scenarios (see Figure 9-4).

R&D needs in the six areas of innovative technologies can be summarized as follows:

- Develop advanced, low cost, efficient solid-state switches (e.g., silicon carbide, gallium nitride) for utility applications
- Develop Nano-Technologies for Utility Applications: (e.g., energy storage, super-insulation materials, fuel cells)
- Develop advanced computer and communication systems (e.g., real-time simulation, robotics)
- Develop Biotechnologies for Utility Applications (e.g., biofuels, biomimesis, carbon capture, corrosion reduction)
- Develop components that support the hydrogen-electric economy (e.g., high pressure electrolyzers)
- Develop DC power production, delivery and utilization systems
- Develop advanced materials(including smart materials, fullerene carbon-60 Buckyballs, high temperature superconducting materials, high temperature turbine blade materials, and advanced corrosion resistant materials)
- Support programs like EPRI’s Innovator’s Circle Program

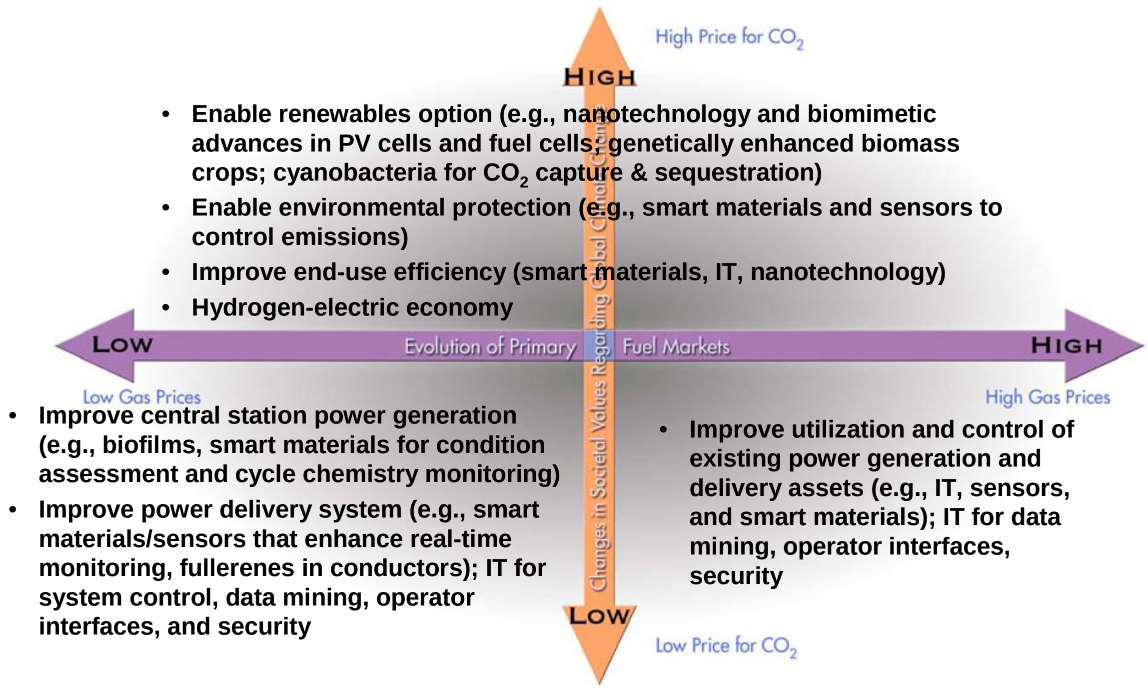

Figure 9-3
Breakthroughs in Various Technologies Will Help Meet Challenges in Each Scenario

Scenario	"Biting the Bullet"	"Double Whammy"	"Supply to the Rescue"	"Digging in Our Heels"
	High CO_2 prices; Low gas prices	High CO_2 prices; High gas prices	Low gas prices; Low CO_2 prices	High gas prices; Low CO_2 prices
Overview and drivers of technology R&D	Focus on applications in renewables, storage, emissions control, and other emerging technologies	Focus on applications in renewables, storage, emissions control, and other emerging technologies	Focus on applications in central station power plants; and power system capacity, monitoring, and control	Focus on applications in central station power plants; and power system capacity, monitoring, and control
Technology R&D Gaps: For each scenario, these represent the critical technology R&D needs in the area of expanding the industry's technology horizon.	Advance biomimetic materials for PV cells, fuel cell cellular membranes	Advance biomimetic materials for PV cells, fuel cell cellular membranes	Advance biofilm technology for corrosion control in power plants	Advance biofilm technology for corrosion control in power plants
	Advance smart materials for real-time power plant control of emissions & cycle chemistry	Advance smart materials for real-time power plant control of emissions & cycle chemistry	Advance smart materials for real-time condition assessment in power plants and power system	Advance smart materials for real-time condition assessment in power plants and power system
Legend: Very critical; Critical; Important. Arrows indicate that the R&D need applies to *more than one scenario*	Advance nanotechnology in PV cells, fuel cells, storage, & catalysts	Advance nanotechnology in PV cells, fuel cells, storage, & catalysts	Advance nanotechnology for conductors and self-healing power system	Advance nanotechnology for conductors and self-healing power system
	Develop low-cost fullerenes in transmission conductors			
	Advance IT for power system monitoring/control (data mining using AI; visualization tools)			
	Advance digital controls & sensors in pwr gen & deliv			
	Hydrogen-electric economy			

Figure 9-4
EPRI Scenario and Technology Development Matrix for Expanding the Industry's Technology Horizon

10
RATING OF R&D NEEDS

The EPRI Research Advisory Council (RAC) met October 24-26, 2006, in part, to review a draft of this document and to perform a priority rating (via its Strategy and Innovation Subcommittees) of the top R&D projects in each of the 20 key R&D technology areas.

To do this, EPRI staff first selected five top R&D needs for each of the 20 areas based on input, in part, from the EPRI Sector Council meetings that occurred in the September-October 2006 timeframe. Hence, a total of 100 R&D needs were available for rating. These R&D needs were grouped into the following four areas:

- Power generation
- Power delivery
- Energy storage and end-use efficiency
- Environment, power and fuel markets, and technology innovation/emerging technologies

Each member of the Committees was given five votes to assign to each of the four groups of R&D needs. Each member was allowed to use more than one vote on a specific R&D need. Hence, each Committee member cast a total of 20 votes for any of the top 100 R&D needs. In this process, those R&D needs with the highest number of votes were judged to be the top rated projects that EPRI should address in it resource allocation processes.

This section contains the detailed results of that rating process. EPRI will use the results of this rating process as one set of important input to allocate funding levels to these R&D needs and to work with stakeholders to ensure that these R&D topics are effectively addressed.

In the power generation group (see Table 10-1), R&D needs in the coal power generation technologies area received the most votes (significantly more than natural gas-fired generation, nuclear, renewables, and distributed energy resources). The following specific R&D needs in the power generation group received the most votes (in decreasing order, with voting results shown below in parentheses):

- Extend life and improve efficiency of existing coal plant technologies (11)
- Demonstrate licensing process and reliability, reduce capital and operating costs, and reduce construction time for future nuclear power plants (7)
- Reduce capital costs and improve efficiency of Integrated Gasification Combined Cycle plants (7)

- Reduce capital costs and improve efficiency of advanced pulverized coal plants (6)
- Improve plant reliability and efficiency (e.g., by reducing materials degradation and improving fuel reliability) for existing nuclear plants (5)

In the power delivery group (see Table 10-2), R&D needs in the transmission and substations area received the most votes (significantly more than grid operations and resource planning, distribution systems, power quality, and physical/cyber security). The following specific R&D needs in the power delivery group received the most votes (in decreasing order, with voting results shown below in parentheses):

- Enhance diagnostics and life extension of aging [transmission and substation] equipment (e.g., transformers) (10)
- Develop high current, high temperature overhead transmission conductors (8)
- Develop cost-effective integrated, inter-regional resource planning tools (7)
- Develop self-healing grid components and control systems (e.g., wide area measurement systems) (6)
- Reduce cost of underground transmission (5)

In the energy storage and end-use efficiency group (see Table 10-3), R&D needs in the electric energy storage area received the most votes (significantly more than end-use energy efficiency, energy service portal, and electricity-based transportation). The following specific R&D needs in the energy storage and end-use efficiency group received the most votes (in decreasing order, with voting results shown below in parentheses):

- Integrate demand-response technologies and direct load management strategies and systems (9)
- Develop and demonstrate flexible AC transmission systems (FACTS) with energy storage (6)
- Develop and demonstrate low-cost plug-in hybrid vehicles in multiple on-road and off-road applications (6)
- Develop electric energy storage value proposition for the re-regulated utility industry (5)

In the group that includes environment, power and fuel markets, and technology innovation (see Table 10-4), R&D needs in the carbon capture, transport, and sequestration area received the most votes (significantly more than technology innovation, power and fuel markets, emissions reduction and control, and environmental science and technology). The following specific R&D needs in the group that includes environment, power and fuel markets, and technology innovation received the most votes (in decreasing order, with voting results shown below in parentheses):

- Develop and apply tools to assess costs and benefits of climate policies to utility industry and member companies (8)
- Demonstrate CO_2 capture, transport, and storage in advanced coal pilot- and full-scale plants (6)

- Develop advanced, low-cost, efficient solid-state switches (e.g., silicon carbide, gallium nitride) for utility applications (6)
- Develop nanotechnologies for utility applications (e.g., energy storage, super-insulation materials, fuel cells) (5)
- Reduce cost of monoethanol amine CO_2 capture process (which currently increases coal plant cost by about 30%) (5)

Table 10-1
Rating of R&D Needs: Power Generation

24 COAL GENERATION	3 NATURAL GAS FIRED GENERATION	9 EXISTING NUCLEAR POWER	9 FUTURE NUCLEAR POWER	10 RENEWABLE RESOURCES	4 DISTRIBUTED ENERGY RESOURCES
Extend life and improve efficiency of existing coal plant technologies 11	Improve CT/CC components (e.g., by improved coatings, adv. repair and new diagnostics) 0	Improve plant reliability and efficiency (e.g., by reducing materials degradation and improved fuel reliability) 5	•Demonstrate licensing process and reliability; reduce capital and operating costs, and reduce construction time 7	Develop renewable value proposition in generation mix (to include renewable portfolio standards and regulatory credits) 4	Reduce cost and increase efficiency of fuel cell hybrid systems (to include combined heat and power systems) 2
Reduce capital costs and improve efficiency of Integrated Gasification Combined Cycle plants 7	Enable CT/CC to run efficiently on mix of North American gas and liquefied natural gas 0	Improve management of low level waste and radioactive materials 0	Expand nuclear fuel resources for long term sustainability 1	Demonstrate emerging technologies to obtain credible cost, reliability and performance metrics 1	Reduce cost and integrate distributed energy resource systems with distributed storage (e.g., battery/ super-capacitors) 0
Reduce capital costs and improve efficiency of advanced Pulverized Coal plants 6	Increase CT/CC efficiency via higher turbine inlet temperature operation 1	Develop integrated spent fuel management syste 3	Develop advanced nuclear generation options (e.g., producing hydrogen) 1	Improve operating efficiency of hydroelectric plants 1	Reduce cost of renewable distributed energy resource systems (e.g., photo voltaic systems) 0
Reduce capital costs and improve efficiency of Fluidized Bed Combustion plants 0	Improve CT/CC turndown efficiency across load range 2	Develop cost-effective, risk-informed asset management and business models 0	Develop and assist in demonstration of closed nuclear fuel cycle 0	Develop credible wind energy forecasting tools 1	Develop and demonstrate distributed uninterruptible power supply (UPS) substation 0
Enable incentive trade-off analyses for early deployment of advanced power generation plants 0	Develop and evaluate advanced CT/CC cycles to lower capital and operating costs 0	Identify role of technology in a work force constrained future 1	Define linkage between nuclear power and electric transportation from an energy security and environmenta perspective 0	Integrate renewables with energy storage, end-use efficiency, transportation, and transmission / distribution systems 3	Define, develop and demonstrate plug-in hybrid fuel cell vehicles as a mobile distributed energy resource 2
Other:	Other:	Other:	Other:	Other:	Other:

Note: Numbers above columns and next to individual projects represent number of votes assigned by RAC members

Table 10-2
Rating of R&D Needs: Power Delivery

TRANSMISSION & SUBSTATIONS (26)	GRID OPERATIONS & RESOURCE PLN'G (16)	DISTRIBUTION SYSTEMS (11)	POWER QUALITY (3)	PHYSICAL AND CYBER SECURITY (5)
Enhance diagnostics and life extension of aging equipment (e.g., transformers) (10)	Develop real-time computerized control systems to minimize cascading blackouts (1)	Develop advanced distribution automation tools (e.g., fault location and restoration) (3)	Improve power quality by advanced designs, equipment, controllers and maintenance tool (1)	Develop hardware tools to protect physical assets from internal or external attacks (0)
Reduce transformer cost and improve sulfur hexafluoride (SF6) circuit breakers (1)	Develop self-healing grid components and control systems (e.g., wide area measurement systems) (6)	Develop advanced tools to improve construction, troubleshooting and repair (1)	Perform power quality benchmarking analyses to include standards development (1)	Develop software tools to protect cyber assets from internal or external attacks (1)
Reduce cost of underground transmission (5)	Implement IntelliGrid tools, including standardized interfaces (0)	Develop solid-state equipment to include the Intelligent Universal Transformer (1)	Develop power quality compatibility tools on AC and DC equipment (0)	Demonstrate Recovery Transformer to rapidly and successfully respond to major outages (1)
Develop high current, high temperature overhead transmission conductors (8)	Demonstrate distributed computing tools for real-time grid transient security assessment (2)	Develop open, standardized and secure communication architecture (2)	Develop power quality tools to integrate distributed generation and storage (1)	Conduct vulnerability-interdependency analyses of electric, communication and fuel sectors (3)
Develop solid-state fault current limiters (2)	Develop cost-effective integrated, inter-regional resource planning tools (7)	Develop an integrated distribution system with storage and distributed generation (4)	Develop economic value proposition for improving power quality (0)	Develop and perform verification of inter-regional emergency test protocols (0)
Other: Efficiency (0)	Other:	Other: Efficiency (0)	Other:	Other:

Note: Numbers above columns and next to individual projects represent number of votes assigned by RAC members

Table 10-3
Rating of R&D Needs: Energy Storage and End-Use Efficiency

ELECTRIC ENERGY STORAGE (19)	END USE ENERGY EFFICIENCY (10)	ENERGY SERVICE PORTAL (16)	ELECTRICITY-BASED TRANSPORTATION (11)
Develop and demonstrate low cost battery and compressed air energy storage systems (3)	Develop and demonstrate increased efficiency ventilation, heating and cooling systems (4)	Establish two-way, standardized, secure communication interface between utility and consumers (3)	Develop and demonstrate low-cost plug-in hybrid vehicles in multiple on-road and off-road applications (6)
Develop electric energy storage value proposition for the re-regulated utility industry (5)	Develop and demonstrate increased efficiency motors and drives (0)	Establish universal, secure communications infrastructure (0)	Document the environmental benefits of plug-in hybrid vehicles (3)
Develop and demonstrate superconducting-storage substation (2)	Develop and demonstrate advanced lighting sources and more efficient lighting systems (4)	Integrate demand-response technologies and direct load management strategies and systems (9)	Validate advanced battery systems for electric drive applications (0)
Develop energy storage integration and evaluation analyses for distributed resources, renewables and the IntelliGrid (3)	Develop and demonstrate cost-effective electro-technologies for improving industrial processes (2)	Integrate and demonstrate IntelliGrid technologies and building and community energy management systems (4)	Develop technologies to lower advanced battery cost and improve efficiency (e.g., Li-Ion batteries) (1)
Develop and demonstrate flexible AC transmission systems (FACTS) with energy storage (6)	Develop and demonstrate efficient DC computer data centers and DC microgrids (0)	Integrate diverse range of consumer, information, security and entertainment services (0)	Evaluate vehicle integrated advanced battery, hydraulic and super-capacitor systems (1)
Other:	Other:	Other:	Other:

Note: Numbers above columns and next to individual projects represent number of votes assigned by RAC members

Table 10-4
Rating of R&D Needs: Technology Innovation, Power and Fuel Markets, and Environment

TECHNOLOGY INNOVATION / EMERGING TECHNOLOGIES (13)	POWER AND FUEL MARKETS (4)	CARBON CAPTURE, TRANSPORT AND SEQUESTRATION (19)	EMISSIONS REDUCTION AND CONTROL (12)	ENVIRONMENTAL SCIENCE AND TECHNOLOGY (11)
Develop Nano-Technologies for Utility Applications: (e.g., energy storage, super-insulation materials, fuel cells) 5	Develop utility industry restructuring plan that addresses need to manage financial risk 0	•Improve CO_2 capture in Integrated Gasification Combined Cycle and advanced fossil plants 3	Reduce cost of emissions control for fossil fuel-fired power generation 4	Establish scientific basis for development of component-based fine particulate matter standard 0
Develop advanced computer and communication systems (e.g., real-time simulation, robotics) 1	Develop innovative ways to minimize cost of capital for market participants by creation of new financial arrangements 0	Demonstrate CO_2 capture, transport, and storage in Advanced Coal pilot and full-scale plants 6	Reduce mercury emissions from fossil power generation by about 95% 3	Address water treatment and management needs, including scientific support for anticipated new effluent guidelines and new water conserving technologies 0
Develop Biotechnologies for Utility Applications (e.g., biofuels, biomimesis, carbon capture, corrosion reduction) 1	Develop mechanisms for efficient, coordinated investments in generation and transmission 3	Reduce cost of monoethanol amine CO_2 capture process (which currently increases coal plant cost by about 30%) 5	Reduce nitrogen oxides and sulfur oxides emissions from fossil power generation to near-zero levels 3	Address environmental impacts of new advanced coal plants such as IGCC as well as distributed generation plants 0
Develop advanced, low cost, efficient solid-state switches (e.g., silicon carbide, gallium nitride) for utility applications 6	Analyze and remedy deficiencies in decentralized market systems (compared to centralized pools) 0	Determine capacity, effectiveness, health and environmental impacts of CO_2 storage options 2	Attain greater than 90% utilization of combustion products from fossil power generation 0	Develop/apply tools to assess costs and benefits of climate policies to utility industry and member companies 8
Develop components that support the hydrogen-electric economy (e.g., high pressure electrolyzers) 0	Assess and improve measures to detect and mitigate market manipulation 1	Explore advanced concepts for carbon capture 3	Address water use limitations by reducing or eliminating water use 2	Resolve the uncertainty of the association between EMF and childhood leukemia 3
Other:	Other:	Other:	Other:	Other:

Note: Numbers above columns and next to individual projects represent number of votes assigned by RAC members

A
TECHNOLOGY R&D "TARGET" AREAS

This appendix contains a composite list of the critical technology R&D needs (i.e., R&D "target" areas) identified in each technology section of this report. The material is organized according to the 20 subject areas covered in the main body of this report.

Power Generation

This subsection contains the technology R&D targets for the area of power generation. See Section 3 for background information and more details.

Coal Power Generation Technologies

- Extend life and improve efficiency of existing coal plant technologies
- Reduce capital costs and improve efficiency of Integrated Gasification Combined Cycle plants
- Reduce capital costs and improve efficiency of advanced Pulverized Coal plants
- Reduce capital costs and improve efficiency of Fluidized Bed Combustion plants
- Enable incentive trade-off analyses for early deployment of advanced power generation plants

Natural Gas Fired Generation Technologies

- Improve CT/CC turndown efficiency across load range
- Increase CT/CC efficiency via higher turbine inlet temperature operation
- Improve CT/CC components (e.g., by improved coatings, adv. repair and new diagnostics)
- Enable CT/CC to run efficiently on <u>mix</u> of North American gas and liquefied natural gas
- Develop and evaluate advanced CT/CC cycles to lower capital and operating costs
- Explore nano-coatings for high temperature turbine blades
- Address gas-electric infrastructure interdependencies that impact forced outages
- Conduct fuel-electric system integration analysis with security of electric infrastructure

Existing Nuclear Power

- Improve plant reliability and efficiency (e.g., by reducing materials degradation and improved fuel reliability)
- Develop integrated spent fuel management system
- Identify role of technology in a work force constrained future
- Improve management of low level waste and radioactive materials
- Develop cost-effective, risk-informed asset management and business models

Future Nuclear Power Capabilities

- Demonstrate licensing process and reliability; reduce capital and operating costs, and reduce construction time
- Expand nuclear fuel resources for long term sustainability
- Develop advanced nuclear generation options (e.g., producing hydrogen)
- Develop and assist in demonstration of closed nuclear fuel cycle
- Define linkage between nuclear power and electric transportation from an energy security and environmental perspective
- Apply nuclear systems to desalination or other process heat applications

Renewable Resources

- Develop renewable value proposition in generation mix (to include renewable portfolio standards and regulatory credits)
- Integrate renewables with energy storage, end-use efficiency, transportation, and transmission / distribution systems
- Demonstrate emerging technologies to obtain credible cost, reliability and performance metrics
- Improve operating efficiency of hydroelectric plants
- Develop credible wind energy forecasting tools

Distributed Energy Resources

- Reduce cost and increase efficiency of fuel cell hybrid systems (to include combined heat and power systems)
- Define, develop and demonstrate plug-in hybrid fuel cell vehicles as a mobile distributed energy resource
- Reduce cost and integrate distributed energy resource systems with distributed storage (e.g., battery/super-capacitors)

- Reduce cost of renewable distributed energy resource systems (e.g., photo voltaic systems)
- Develop and demonstrate distributed uninterruptible power supply (UPS) substation
- Integrate DER with flexible electric distribution topologies (including microgrids and the IntelliGrid) to improve power reliability and quality; and integrate with the energy service portal

Electric Energy Storage

This subsection contains the technology R&D targets for the area of electric energy storage. See Section 4 for background information and more details.

- Develop and demonstrate flexible AC transmission systems (FACTS) with energy storage
- Develop electric energy storage value proposition for the re-regulated utility industry
- Develop and demonstrate low cost battery and compressed air energy storage systems
- Develop energy storage integration and evaluation analyses for distributed resources, renewables and the IntelliGrid
- Develop and demonstrate superconducting-storage substation
- Develop and demonstrate renewable generation options with energy storage
- Document the successful operation and economic benefits of existing pumped hydro, battery, and compressed air energy storage plants

Environment

This subsection contains the technology R&D targets for the environment area. See Section 5 for background information and more details.

Carbon Capture, Transport and Sequestration

- Demonstrate CO_2 capture, transport, and storage in Advanced Coal pilot and full-scale plants
- Reduce cost of monoethanol amine CO_2 capture process (which currently increases coal plant cost by about 30%)
- Explore advanced concepts for carbon capture
- Improve CO_2 capture in Integrated Gasification Combined Cycle and advanced fossil plants
- Determine capacity, effectiveness, health and environmental impacts of CO_2 storage options
- Develop tools that enable economic evaluation of various sequestration options

Emissions Reduction and Control

- Reduce cost of emissions control for fossil fuel-fired power generation
- Reduce mercury emissions from fossil power generation by about 95%
- Reduce nitrogen oxides and sulfur oxides emissions from fossil power generation to near-zero levels
- Address water use limitations by reducing or eliminating water use
- Attain greater than 90% utilization of combustion products from fossil power generation
- Ensure consistent particulate emissions at low levels over all fuels and load levels
- Document and report on the emission reduction value of electric transportation in on-road and off-road applications

Environmental Science and Technology

- Develop/apply tools to assess costs and benefits of climate policies to utility industry and member companies
- Resolve the uncertainty of the association between EMF and childhood leukemia
- Establish scientific basis for development of component-based fine particulate matter standard
- Address water treatment and management needs, including scientific support for anticipated new effluent guidelines and new water conserving technologies
- Address environmental impacts of new advanced coal plants such as IGCC as well as distributed generation plants
- Develop tools for component lifecycle and total ecosystem analysis of emissions
- Develop models for optimization of strategies that address air-water-climate interactions
- Explore nanotechnology for treatment of low-level liquid waste streams

Power Delivery

This subsection contains the technology R&D targets for the area of power delivery. See Section 6 for background information and more details.

Transmission & Substations

- Enhance diagnostics and life extension of aging equipment (e.g., transformers)
- Develop high current, high temperature overhead transmission conductors
- Reduce cost of underground transmission

- Develop solid-state fault current limiters
- Reduce transformer cost and improve sulfur hexafluoride (SF6) circuit breakers
- Develop advanced asset management tools
- Develop high voltage alternating current (AC) and direct current (DC) lines
- Develop advanced technologies that enable superconducting substations
- Develop advanced power-electronics-based controllers (i.e., Flexible AC Transmission Systems technologies) for management of large disturbances, including use of advanced dielectric materials
- Develop low-cost, reliable remote sensors for underground and overhead transmission systems
- Integrate transmission and substation advancements with IntelliGrid technologies

Grid Operations and Resource Planning

- Develop cost-effective integrated, inter-regional resource planning tools
- Develop self-healing grid components and control systems (e.g., wide area measurement systems)
- Demonstrate distributed computing tools for real-time grid transient security assessment
- Develop real-time computerized control systems to minimize cascading blackouts
- Implement IntelliGrid tools, including standardized interfaces
- Develop next-generation control centers
- Develop fast simulation and modeling, alarm management, adaptive grid recovery systems and integration with security of electric infrastructure technologies
- Develop advanced tools and methods for rapid, efficient power system restoration

Distribution Systems

- Develop an integrated distribution system with storage and distributed generation
- Develop advanced distribution automation tools (e.g., fault location and restoration)
- Develop open, standardized and secure communication architecture
- Develop advanced tools to improve construction, troubleshooting and repair
- Develop solid-state equipment to include the Intelligent Universal Transformer
- Develop flexible electric distribution system topologies (e.g., adaptive islanding, microgrids, and adaptive reconfiguration systems)
- Develop and implement intelligent sensors and monitoring systems

- Develop and demonstrate five-wire distribution system
- Integrate smart metering concepts to enable consumers and utilities to maximize the benefits of night-time recharging of plug-in electric vehicles

Power Quality

- Improve power quality by advanced designs, equipment, controllers and maintenance tools
- Perform power quality benchmarking analyses to include standards development
- Develop power quality tools to integrate distributed generation and storage
- Develop power quality compatibility tools on AC and DC equipment
- Develop economic value proposition for improving power quality

Physical and Cyber Security

- Conduct vulnerability-interdependency analyses of electric, communication and fuel sectors
- Develop software tools to protect cyber assets from internal or external attacks
- Demonstrate Recovery Transformer to rapidly and successfully respond to major outages
- Develop and perform verification of inter-regional emergency test protocols
- Develop hardware tools to protect physical assets from internal or external attacks
- Ensure cyber protection of Supervisory Control and Data Acquisition (SCADA), Energy Management System (EMS), Distributed Control Systems (DCS), and communications systems and interfaces
- Conduct comprehensive grid equipment cyber vulnerability assessments; and develop wide-scale cyber threat monitoring and alert system
- Provide tools, and conduct and improve cyber and physical security training and "red teaming" exercises
- Develop and deploy grid security monitoring, disturbance detection, and disturbance location and mitigation system
- Establish industry-wide communication and alert system

End Uses of Electricity

This subsection contains the technology R&D targets for the area of end uses of electricity. See Section 7 for background information and more details.

Energy Service Portal

- Integrate demand-response technologies and direct load management strategies and systems
- Integrate and demonstrate IntelliGrid technologies and building and community energy management systems
- Establish two-way, standardized, secure communication interface between utility and consumers
- Establish universal, secure communications infrastructure
- Integrate diverse range of consumer, information, security and entertainment services

End-Use Energy Efficiency

- Develop and demonstrate increased efficiency ventilation, heating and cooling systems
- Develop and demonstrate advanced lighting sources and more efficient lighting systems
- Develop and demonstrate cost-effective electro-technologies for improving industrial processes
- Develop and demonstrate increased efficiency motors and drives
- Develop and demonstrate efficient DC computer data centers and DC microgrids
- Develop improved compressors, components, refrigerants and cycles; advanced district heating and cooling systems; and magnetocaloric and thermoelectric cooling
- Assess opportunities for improved residential and commercial appliances, including advanced office equipment and smart household appliances
- Integrate IntelliGrid technologies into the existing electricity infrastructure

Electricity-Based Transportation

- Develop and demonstrate low-cost plug-in hybrid vehicles in multiple on-road and off-road applications
- Document the environmental benefits of plug-in hybrid vehicles
- Develop technologies to lower advanced battery cost and improve efficiency (e.g., Li-Ion batteries)
- Evaluate vehicle integrated advanced battery, hydraulic and super-capacitor systems
- Validate advanced battery systems for electric drive applications
- Expand the knowledge base required for battery monitoring and optimization analyses
- Develop low-cost reliable vehicle controls, mechanical systems, power electronics, and charging systems
- Develop nanotechnology-enabled batteries/supercapacitors

- Conduct mobile distributed generation analysis
- Apply advances to commercial transportation, mass transit, and construction equipment

Power and Fuel Markets

This subsection contains the technology R&D targets for the area of power and fuel markets. See Section 8 for background information and more details.

- Develop mechanisms for efficient, coordinated investments in generation and transmission
- Assess and improve measures to detect and mitigate market manipulation
- Develop utility industry restructuring plan that addresses need to manage financial risk
- Develop innovative ways to minimize cost of capital for market participants by creation of new financial arrangements
- Analyze and remedy deficiencies in decentralized market systems (compared to centralized pools)
- Develop advanced market simulation and modeling tools, including power, fuel and emission price volatility analyses, and emission trading analysis
- Develop a decision-support framework for technology investment, capacity planning, unit retirements and mothballing, and greenhouse gas emissions reduction
- Devise new forms of service contracts and method to design new service programs for retail markets
- Gather data and conduct economic analyses to support cost effective decision making for fuels markets

Technology Innovation/Emerging Technologies

This subsection contains the technology R&D targets for the area of technology innovation/emerging technologies. See Section 9 for background information and more details.

- Develop advanced, low cost, efficient solid-state switches (e.g., silicon carbide, gallium nitride) for utility applications
- Develop Nano-Technologies for Utility Applications: (e.g., energy storage, super-insulation materials, fuel cells)
- Develop advanced computer and communication systems (e.g., real-time simulation, robotics)
- Develop Biotechnologies for Utility Applications (e.g., biofuels, biomimesis, carbon capture, corrosion reduction)
- Develop components that support the hydrogen-electric economy (e.g., high pressure electrolyzers)

- Develop DC power production, delivery and utilization systems
- Develop advanced materials(including smart materials, fullerene carbon-60 Buckyballs, high temperature superconducting materials, high temperature turbine blade materials, and advanced corrosion resistant materials)
- Support programs like EPRI's Innovator's Circle Program

B

WILD CARDS AND INSTITUTIONAL CHALLENGES

The scenarios in this report are defined by the combinations of high and low natural gas prices, and high and low environmental (and other externality) importance. However, a broad range of potential discrete occurrences, besides extreme outcomes of these two parameters, could have a significant impact on the electric power industry. These “wild cards” are not explicitly discussed in this report, but are listed here to indicate the range of occurrences that are possible. While beyond the scope of this report, plans to enable preparation for, and reaction to, these occurrences are needed.

Following is a potential list of wild cards that are associated with technological changes that could have a significant impact on the electric power industry (mostly in the mid to long term time period):

- A room-temperature superconductor is discovered.
- A nanotech breakthrough occurs, enabling micro-inverters to be deployed so that microgrids can be implemented with low losses and at low cost.
- A breakthrough occurs in the biological production of hydrogen that permits substantial use of hydrogen as a transportation fuel and for electricity generation via fuel cells.
- A battery technology breakthrough occurs for electricity-based transportation (i.e., low cost and long life systems are commercially available) with flow-down benefits to use of battery systems for distributed energy resources.
- Advanced solid-state switch material becomes available that enables power electronics-based technology to be reduced to one-third of its current cost.
- Significant advances in end-use efficiency technology are quickly perfected (e.g., advanced mercury-free light sources and thermoelectric and magnetocaloric discoveries for cooling and refrigeration) and institutional changes occur rapidly (e.g., regulatory mandated integrated resource planning that aggressively increases the implementation of demand response and energy efficiency programs).
- A new generation technology is discovered (e.g., small modular nuclear plants known as “tri-alpha technology”).
- Ocean-based carbon dioxide (CO_2) storage becomes commercially available and publicly acceptable.
- New materials and/or blade cooling methods are developed that enable turbine inlet temperatures to rise by at least 500°F/260°C.

- Reliable, efficient energy storage technology is developed at one-third the cost of existing storage systems, which enables deployment throughout the grid and end-use sectors.
- Distributed generation systems are developed at one-third the cost of existing systems, with acceptable emissions, which enables them to be deployed commercially.
- The self-healing grid is successfully demonstrated in the next ten years.
- A very large oil and/or gas basin is discovered in a politically stable part the world.

Following is a potential list of wild cards associated with external events (some political and some social) that could have a significant impact on the electric power industry:

- Significant world-wide climate change occurs in the world (over the next ten years), which causes widespread public outcries.
- A major nuclear accident occurs (anywhere in the world).
- The opening of Yucca Mountain repository in the U.S. continues to be delayed.
- An unanticipated consequence of a critical new technology is discovered (e.g., a large number of IGCC plants have a new pollution consequence not previously addressed; underground sequestration of CO_2 is demonstrated to not be feasible, or public reception of CO_2 storage as dangerous “pollution dumping” stops deployment in its tracks).
- Real load growth (peak power and energy consumption) significantly exceeds forecasts, taxing the power system.
- Heat waves cause large transmission and distribution networks to be overloaded for several days.
- A series of widespread North American power system blackouts occur
- A coordinated physical/cyber terrorist attack occurs on the wide area power system that causes large regional blackouts of sustained duration.
- A terrorist attack occurs on a major U.S. infrastructure that is not power system related (e.g., a subway station in a major city; water supply disruption; or assassination of a government leader). This event is large enough to cause collateral impacts to the electricity sector (e.g., government security regulations impact electric utility operations).
- A bio-pandemic occurs (e.g., avian flu).
- A cyber hacker disables a utility SCADA/EMS system for an extended period of time.
- Widespread regulatory changes facilitate/mandate the use of microgrids with distributed energy resources.

This report also does not focus on challenges and needs related to institutional, political, or social changes; other financial uncertainties; or the role of public opinion. Although these influences will clearly affect future outcomes, detailed discussion of them is beyond the scope of this report. Based on a review of the content of this report, the following uncertainties of this type are likely to pose significant impacts and could be the subject of future, focused scenario development and analysis by EPRI and others:

- Will federal and state regulators tend to accelerate industry restructuring, deregulation, and a market-based approach; will they tend to advocate a return to regulation across the industry; or will they tend to impose a hybrid of these two extremes?
- Will a system of encouraging or mandating needed investment in transmission assets (and coordination with generation assets) be established, and will it function properly?
- Will regulators or government impose much more stringent physical/cyber security regulations on the industry?
- Will significant and rapid financial impacts (e.g., macroeconomic shifts or dramatic changes in the price or availability of some fuel or fuels) become a disruptive influence?
- Will major global political factors have an impact?
- Will social change (e.g., shifting public opinion and/or demographics) or regulations force a significantly increased role for "green power," (e.g., end-use energy efficiency, renewables, and electricity-based transportation), storage, and/or distributed energy resources?
- Will major social change (e.g., a strong consumer movement) accelerate a "consumer revolution" that requires a shift in electric power industry priorities?
- Will rapid, unanticipated changes in the macroeconomy, meteoric growth in specific industries, major technological breakthroughs outside the industry, or other factors necessitate faster than anticipated need to address power reliability and power quality issues?
- Will the American people and regulators accept construction of a significant number of new nuclear power plants?
- Will the Yucca Mountain repository be commissioned?

C
ACRONYMS

ABC	Ammonium Bicarbonate
AC	Alternating Current
ADA	Advanced Distribution Automation
AGR	Acid Gas Removal
ALARA	As Low As Reasonably Achievable
ALWR	Advanced Light Water Reactor
AMR	Automatic Meter Reading
ASTM	American Society of Testing Materials
ATC	Available Transfer Capability
BACT	Best Available Control Technologies
BEV	Battery-Electric Vehicles
BIES	Building Integrated Energy Systems
BOFA	Boosted Over-Fire Air
BPA	Bonneville Power Administration
BPL	Broadband over Power Line
BWR	Boiling Water Reactor
CAES	Compressed Air Energy Storage
CAR	Community Activity Room
CCURB	Corrosion Control Using Regenerative Biofilms

CDHS	California Department of Health Services
CH_3Hg	Monomethylmercury
CH_4	Methane
CHAT	Cascaded Humidified Advanced Turbine
CHP	Combined Heat and Power
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COE	Cost Of Electricity
CT	Combustion Turbine
CT/CC	Combustion Turbine/Combined Cycle
CURC	Coal Utilization Research Council
DA	Distribution Automation
DC	Direct Current
DCS	Distributed Control Systems
DER	Distributed Energy Resources
DLC	Direct Load Control
DLN	Dry Low NO_X Burner
DOE	U.S. Department Of Energy
ECBM	Enhanced Coal Bed Methane
EDV	Electric Drive Vehicles
EIPP	Eastern Interconnection Phasor Project
EMF	Electric and Magnetic Fields
EMS	Energy Management Systems

EOR	Enhanced Oil Recovery
EPA	U.S. Environmental Protection Agency
EPRI	Electric Power Research Institute
ESP	Electrostatic Precipitator
ETAC	Energy Technology and Analysis Center
EV	Electric Vehicle
FACTS	Flexible AC Transmission System
FB	Fluidized Bed
FBC	Fluidized Bed Combustion
FERC	Federal Energy Regulatory Commission
FGD	Flue Gas Desulfurization
FOAKE	First-Of-A-Kind Engineering
GaN	Gallium Nitride
GAO	Government Accounting Office
GHG	Greenhouse Gas
GPS	Global Positioning Satellite
H_2S	Hydrogen Sulfide
HAP	Hazardous Air Pollutants
HAT	Humid Air Turbine
HBU	High Burn-Up
Hg	Mercury
HHV	Higher Heating Value
HRSG	Heat Recovery Steam Generator

HVAC	Heating, Ventilating and Air Conditioning
HVDC	High Voltage Direct Current
I&C	Instrumentation and Control
IARC	International Agency for Research on Cancer
ICNIRP	International Commission on Non-Ionizing Radiation Protection
IEC	International Electrotechnical Commission
IED	Intelligent Electronic Devices
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated Gate Bipolar Transistors
IGCC	Integrated Gasification Combined Cycle
IGCT	Integrated Gate-Commutated Thyristors
INL	Idaho National Laboratory
INPO	Institute of Nuclear Power Operations
IOU	Investor Owned Utility
IP	Internet Protocol
ISI	Infrastructure Security Initiative
ISO	Independent System Operator
IT	Information Technology
ITM	Ion Transport Membranes
IUT	Intelligent Universal Transformer
LCD	Liquid Crystal Displays
LHV	Lower Heating Value
Li-ion	Lithium-Ion

LNG	Liquefied Natural Gas
LSE	Load Serving Entity
MEA	Monoethanol Amine
N_2O	Nitrous Oxide
NDE	Non-Destructive Evaluation
NERC	North American Electric Reliability Council
NH_3	Ammonia
NIEHS	National Institute of Environmental Health Sciences
NiMH	Nickel-Metal Hydride
NIMBY	Not In My Back Yard
NO_x	Nitrogen Oxides
NRC	Nuclear Regulatory Commission
NRPB	National Radiological Protection Board
NTP	Non-Thermal Plasma Technologies
NZE	Near Zero Emissions
O&M	Operation And Maintenance
OEM	Original Equipment Manufacturer
OFA	Over-Fire Air
PC	Pulverized Coal
PDC	Phasor Data Concentrators
PHEV	Plug-in Hybrid Electric Vehicle
PM	Particulate Matter
PMU	Phasor Measurement Unit

ppm	Parts Per Million
Ppmv	Parts Per Million By Volume
ppmw	Parts Per Million By Weight
PQ	Power Quality
PRA	Probabilistic Risk Assessment
PRB	Powder River Basin
PV	Photovoltaics
PWR	Pressurized Water Reactor
RD&D	Research, Development and Demonstration
RE	Renewable Energy
RP	Radiological Protection
RPS	Renewable Portfolio Standards
RTO	Regional Transmission Organization
RTU	Remote Telemetry/Terminal Units
SC	Supercritical
SCADA	Supervisory Control And Data Acquisition
SCR	Selective Catalytic Reduction
SF_6	Sulfur Hexafluoride
SMES	Superconducting Magnetic Energy Storage
SMS	Smart Materials and Structures
SiC	Silicon Carbide
SOFC	Solid Oxide Fuel Cell
SO_x	Sulfur Oxides

SRU	Sulfur Recovery Unit
T&D	Transmission & Distribution
TBC	Thermal Barrier Coating
TCP/IP	Transmission Control Protocol/Internet Protocol
TMDL	Total Maximum Daily Load
TRI	Toxic Release Inventory
UBC	Unburned Carbon
UCA	Utility Communication Architecture
UHVDC	Ultra High Voltage Direct Current
UNFCCC	United Nations Framework Convention on Climate Change
UPS	Uninterruptible Power Supply
USC	Ultra-Supercritical
USC PC	Ultra-Supercritical Pulverized Coal
VAR	Voltage Amp Reactive
VHTR	Very High Temperature Reactor
VOC	Volatile Organic Compounds
VRB	Vanadium Redox Battery
WACS	Wide Area stability and voltage Control System
WAMS	Wide Area Measurement System
WAPA	Western Area Power Administration

D BIBLIOGRAPHY

Dalton, Stuart. EPRI. "Efficiency of Generation – The Role of Very Efficient/Low Emission Coal." Panel presentation at the Clearwater Coal Conference, May 23, 2006.

Douglas, John. "Putting Wind on the Grid." *EPRI Journal,* spring 2006, pp. 6-15.

Electric Power Research Institute (EPRI), 2007 Portfolio, http://www.epri.com/portfolio/default.aspx?year=2007

EPRI. *Distributed Energy Resources: Current Landscape and a Roadmap for the Future*. EPRI report number 1008415, November 2004.

EPRI-DOE Handbook of Electricity Storage for Transmission and Distribution Applications. Final report, EPRI report number 1001834, December 2003.

EPRI. *Comparison of Storage Technology for Distributed Resource Applications*. EPRI report number 1007301, 2003.

EPRI. *Technology Review and Assessment of Distributed Energy Resources, Distributed Energy Storage*. EPRI report number 1012983, 2005.

EPRI. *Economic Costs and Benefits of Distributed Energy Resources*. EPRI report number 1011305, December 2004.

EPRI. *Technology Review and Assessment of Distributed Energy Resources*. EPRI report number 1010525, 2005.

EPRI. *Technologies to Achieve Near-Zero Emissions Goals: Concepts and Technical Challenges.* EPRI report number 1010335, March 2006.

EPRI. *Status and Performance of Best Available Control Technologies.* EPRI report number 1008114, March 2005.

EPRI. "Generation Technologies for a Carbon-Constrained World." *EPRI Journal,* summer 2006.

EPRI. "Climate Policy Gets Down to Business." *EPRI Journal,* summer 2006.

EPRI. "Turning on Energy Efficiency." *EPRI Journal,* summer 2006.

EPRI. *Electricity Technology Roadmap: 2003 Summary and Synthesis, Power Delivery and Markets.* EPRI report number 1009321, November 2003.

EPRI. *Power Delivery System of the Future, A Preliminary Estimate of Costs and Benefits.* EPRI report number 1011001, July 2004.

EPRI. *Program on Technology Innovation: Opportunities for Advancing End-Use Energy Efficiency,* EPRI report number 1012003, May 2005.

EPRI. *Electricity Technology Roadmap, 2003 Summary and Synthesis.* EPRI report number 1010929, 2003.

EPRI. *Electric Power Industry Technology Scenarios: Preliminary Results.* EPRI report number 1013016, 2005.

Gellings, Clark W., and Steve Hoffman, "The Top 10 Utility Tech Challenges," *Public Utilities Fortnightly,* August 2006, pp. 46-51.

Haase, Paul. "Mercury Control for Coal-Fired Power Plants." *EPRI Journal*, summer 2005, pp. 17-25.

Haase, Paul. "IntelliGrid: A Smart Network of Power." *EPRI Journal*, fall 2005, pp. 26-32.

Moore, Taylor. "Coal-Based Generation at the Crossroads." *EPRI Journal*, summer 2005, pp. 6-15.

Moore, Taylor and John Douglas. "Energy Storage: Big Opportunities on a Smaller Scale." *EPRI Journal*, spring 2006, pp. 16-23.

"Potential for Improvement in Gasification Combined Cycle Power Generation with CO_2 Capture." IEA Greenhouse Gas R&D Programme, PH4-19. May 2003.

Rastler, Dan. "Are Distributed Energy Resources Gaining Traction?" *Public Utilities Fortnightly*, February 2005, pp. 48-53.

Sanna, Lucy. "Driving the Solution: The Plug-in Hybrid Vehicle," *EPRI Journal*, fall 2005, pp. 8-17.

Syfers, Robert. "EMF and Childhood Leukemia." *EPRI Journal*, spring 2006, pp. 24-31.

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