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

Volume 1 - Executive Summary

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
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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. This 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.

This executive summary report (Volume 1) provides an overview of the project, recommended timelines for the 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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EXECUTIVE SUMMARY

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. 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 action plans 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*[2] project. It involved 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 uncertainties inherent in the technology R&D planning process.

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

[1] Electricity Technology Roadmap, 2003 Summary and Synthesis, EPRI report 1010929, 2003.
[2] Electric Power Industry Technology Scenarios: Preliminary Results, EPRI report 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. 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.

Scenarios can serve the role of helping to generate ideas and options in response to changing business conditions. They can stretch thinking, generate inquiry and learning, and provide a sense for areas in which innovation is needed. The following two key drivers relevant to the electricity sector were used to define the scenarios: 1) the future price of natural gas, and 2) future perceived societal value regarding global climate change (manifested in the form of the price of CO_2 emissions). The combinations of high and low values for each of these two factors defines four scenarios (see Figure 1-1).

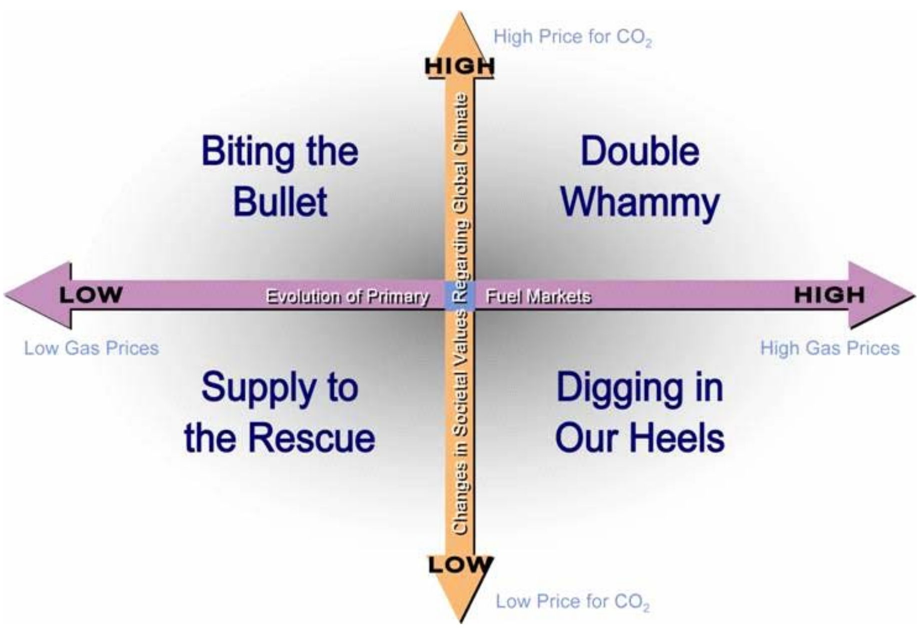

Figure 1-1
High and low values for natural gas prices and importance of environmental and other externalities (manifested in the form of CO_2 prices) define the four scenarios used in this report.

Overview of Scenarios

This section briefly describes each of the four scenarios.

The "Digging in Our Heels" Scenario

In the "Digging in our Heels" scenario (high natural gas prices and low price for CO_2 emissions), 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 emissions 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.

In this scenario, 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. Although U.S. consumers maintain a high and improving standard of living, the electric utility industry does not keep pace with the rest of the economy. Concerns for full cost recovery and tepid customer 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 (primarily coal- and nuclear-based) dominates decisions regarding new generating capacity at the expense of distributed generation. 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. This scenario reflects some current conditions in parts of the U.S.

The "Supply to the Rescue" Scenario

In the "Supply to the Rescue" scenario (low natural gas prices and low price for CO_2 emissions), government and industry make large investments that lead to ample supplies of electricity and stable and 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 debatable connection between energy use and climate change.

In this scenario, technological innovation continues to move the U.S. toward a more knowledge-based economy with more efficient use of energy resources and moderate overall economic growth. To address national security concerns, the U.S. moves ahead quickly with infrastructure development to enable the importation of more natural gas. Developing and implementing liquefied natural gas (LNG) technology moves to a level of international cooperation that mirrors that in oil development and transportation. Due to its low price, natural gas is the most competitive choice as a fuel for power generation, and 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.

The "Double Whammy" Scenario

The "Double Whammy" scenario (high gas prices and high price for CO_2 emissions) encompasses a significant change in beliefs and values for the majority of Americans and industry, as well as a shift in government policy, toward the position that anthropogenic changes in global climate are occurring, that they are harmful, and that they must be addressed soon.

This scenario greatly accelerates investment and innovation. International consensus and a mutually supportive business atmosphere evolves between business leaders, politicians, and consumers who 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. Advanced 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 gas-fired generation. This scenario reflects current conditions in the European Union and Japan. Currently, California and New England seem to be headed in the direction of this scenario.

The "Biting the Bullet" Scenario

The "Biting the Bullet" scenario (low gas prices and high price for CO_2 emissions) encompasses the need to take painful actions in the near term to forestall even more painful consequences in the future. Society attempts to deal with a series of world-scale, climate-related events, and wide public acceptance that climate change is occurring and must be slowed or halted. U.S. policy makers 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. The policy changes moderately reduce demand for primary fuels. With slower economic growth, fuel prices moderate and begin to decline.

In this scenario, 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. Technology innovations in digital applications, bioscience, 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. And, 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. This scenario reflects current conditions in France, with its nuclear mandate.

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 these four scenarios. This report is not intended to include an exhaustive list of technology R&D topics or their costs, or to set a final set of technology 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 discussed to a limited extent in this report. In the future, EPRI will estimate the costs to conduct the recommended R&D and the recommended roles for stakeholders associated with the identified R&D efforts.

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. In addition to identifying the critical technology R&D needs, this report proposes preliminary timelines for a wide set of R&D topics. 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 utility industry.

Conclusions: Critical Technology R&D Needs

Overview

The process of identifying critical technology R&D needs in the next 20 years in the electric utility industry has resulted in significant challenges to be addressed. This section summarizes the most critical technology R&D needs in the following seven areas:

- Power generation, including alternative energy technologies
- Electric energy storage
- Environmental challenges
- Power delivery
- End use of electricity
- Power and fuel markets
- Technology innovation and emerging technologies

Volume 2 of this report contains more information on R&D needs in each of these technology areas, including relevant background material and the mapping of each R&D need to one or more of the specified "what-if" scenarios.

The Power Generation Mix

Important R&D areas come to light when examining the key issues and/or uncertain variables that affect the future power generation mix. A recent analysis conducted by EPRI's Energy Technology and Analysis Center (ETAC) concluded that the major uncertainties are the following:

- The future price of natural gas
- The future cost of carbon dioxide (CO_2) emissions
- The storage of spent nuclear fuel (i.e., public acceptance is uncertain)
- Climate change and the technical viability of CO_2 capture and sequestration

The first two of these uncertainties are reflected in the axes that define the four scenarios used in this report. Examination of the scenario-by-scenario power generation needs (see Figure 1-2) reveals what most planners have known for a long time: only a diverse portfolio of power generation technologies will meet the nation's energy needs. While these four uncertainties will certainly shape the outcome of the future generation mix, R&D efforts across generation technologies are likely to narrow the differences between the cost effectiveness and environmental value of the various options. Table 1-1 lists the timing of major critical R&D needs in the power generation area.

The abundance of coal reserves in the U.S., and the fact that coal-based generation accounts for about one-half of all U.S. electric energy produced, highlights the need for increased attention on coal-fired options for the present (via R&D that enhances the existing fleet) and the future. The flexibility of integrated gasification combined cycle (IGCC) plants to capture CO_2 at relatively reasonable cost ensures its role in the future generation mix, but R&D must reduce its capital cost and improve its efficiency to ensure success. The efficiency of next generation pulverized coal plants must also be improved via materials advances that enable higher temperature operation.

At the same time, neglecting needed advances in natural gas-fired generation would not be prudent. Gas-fired plants offer the lowest investment requirements of any new type of commercially-available central station plant. They are very efficient and have a small plant footprint. They can be readily sited, and can be constructed in a much shorter period of time than other large-scale power generation options. Most combustion turbines (CTs) today are capable of near zero emissions of nitrogen oxides (NO_x), sulfur oxides (SO_x), carbon monoxide (CO), particulate matter, and hazardous air pollutants (HAPs). Primary R&D needs for CTs include increasing efficiency, enabling fuel flexibility (with syngas and liquefied natural gas fuels), enabling more efficient part-load turndown, and enhancing long term durability and reliability.

Power Generation Technology: Critical R&D Needs

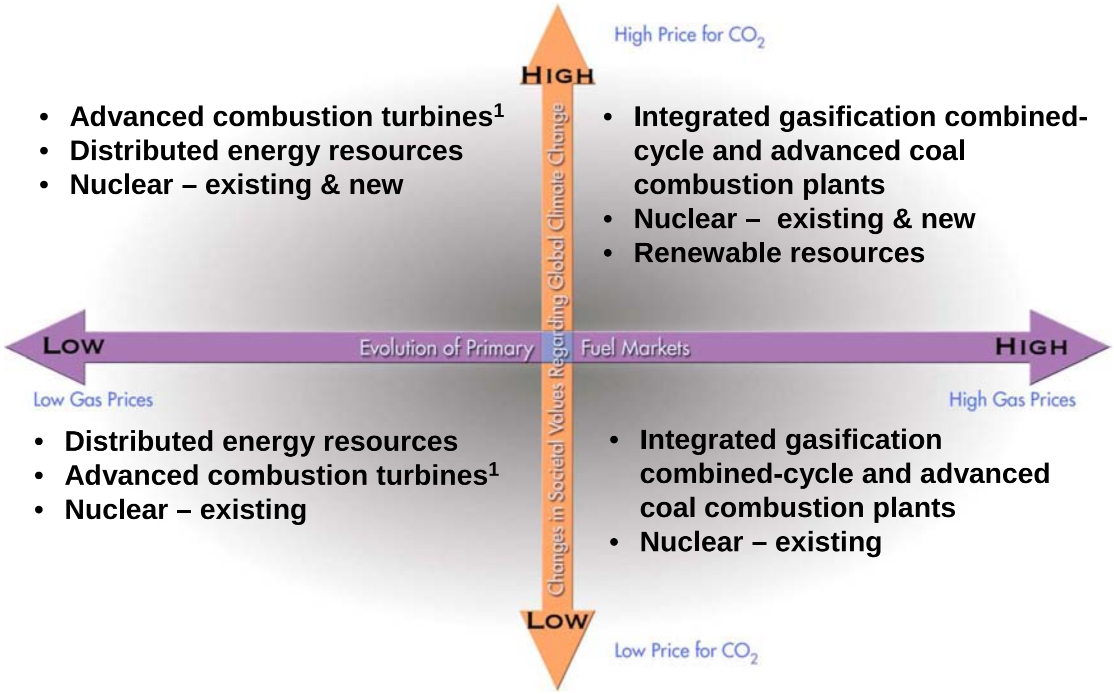

Figure 1-2
The scenario analysis reveals that only a mix of power generation technologies will meet the nation's energy needs.

Movement up from the scenario in the lower right quadrant ("Digging in our Heels") expands power generation options. Changes in economic conditions from the lower right quadrant are needed for distributed energy resources, renewable resources, nuclear power, combustion turbines, and carbon capture/sequestration to become more critical from the R&D perspective. Note 1: R&D is needed to improve combustion turbine efficiency, fuel flexibility, turndown, and long term durability and reliability.

Regarding the third item in the bulleted list on page 1-6 above, resolving the issue of spent nuclear fuel storage is crucial to the continued operation of the existing fleet of nuclear power plants, as well as to the expansion of nuclear power in the U.S. And nuclear power, in turn, can play a critical role in cost-effectively reducing CO_2 emissions in the "Double Whammy" (high gas prices and high CO_2 prices) scenario. While this complex issue involves institutional and political aspects, technology R&D can certainly inform this process. For example, R&D needs include an acceptance criterion for transportation of spent fuel, methods of transportation and storage of multi-purpose canisters at the Yucca Mountain repository, and reactors that can burn minor actinides (i.e., heavy metal elements with atomic number 89 to 91) in an economic closed nuclear fuel cycle.

Table 1-1
Timeline of Critical R&D Needs for the Areas of Power Generation and Electric Energy Storage[3]

Critical R&D Needs: Power Generation and Electric Energy Storage	Near Term: 1 - 5 Yrs	Mid Term: 6 -10 Yrs	Long Term: 11 - 20 Yrs
Extend life and improve efficiency of **existing coal plants**	Develop and demonstrate new life extension and efficiency improvements	Fleet-wide deployment and evaluation	Long-term reliability and durability monitoring and analyses
Reduce cost and improve efficiency of **integrated gasification combined cycle** (IGCC) in 3 rounds of system integration demonstrations	Round 1 – Initial demonstration of IGCC plant with carbon capture	Round 2 – Interim demo of lower cost, higher efficiency, carbon capture IGCC plant	Round 3 – Final demonstration of lower cost, higher efficiency IGCC plant with carbon capture
Reduce cost and improve efficiency of advanced **pulverized coal** (via materials advances) and supercritical fluidized-bed combustion in 3 rounds of system integration demonstrations	Round 1– Initial demo of higher-temperature operation in advanced pulverized coal plant	Round 2 – Interim demo of progressively higher temperature operation in advanced pulverized coal plant	Round 3 – Final demonstration of lower cost, higher efficiency advanced pulverized coal plant
Improve fuel flexibility, efficiency, and turndown of **combustion turbine** (CT) and CT/combined cycle (CTCC) in 3 rounds of system integration demonstrations	Round 1– Initial demonstration of enhanced CTCC plant	Round 2 – Interim demonstration of further enhancements of CTCC plant	Round 3 – Final demonstration of CTCC plant with improved fuel flexibility, efficiency, and turndown
Develop and demonstrate a safe, integrated **spent nuclear fuel** management system	Centralized interim waste storage	Yucca Mountain monitoring & capacity expansion analyses	Long-term repository monitoring and management
Ensure safe, reliable operation of **existing nuclear plants** (materials, fuel reliability, nondestructive evaluation, instrumentation, controls)	Develop and demonstrate new life extension techniques	Fleet-wide deployment and evaluation	Long-term reliability and durability monitoring and analyses
Build **new nuclear plants** by demonstrating licensing process, reliability; and reducing capital costs, operating costs, and construction time	Initial development of next generation plant design	Pilot plant construction and testing/evaluation	First commercial next generation plant
Develop and demonstrate lower cost **distributed energy resources (DER), renewables, and energy storage** technologies; develop value propositions; resolve interconnection issues; and capitalize on integration opportunities (e.g., DER/ energy storage; power electronics/energy storage)	Pilot-scale demonstrations (flow/sodium sulfur battery demos, compressed air energy storage using porous rock air storage, integrated wind- storage plant)	Initial full-scale field demonstrations (commercial-scale demo of distributed fuel cell with storage plant; power electronics-based controllers with storage demo)	Wide full-scale deployment (wind and photovoltaic plants; compressed air energy storage with above ground pipe air storage; fuel cell plants; supercapacitor energy storage)

[3] This timeline and other timelines in the report were developed based on interviews with subject matter experts, review of documents, and expert judgment.

Unrealized Potential of Alternative Energy Technologies

Thirty years ago, renewable sources of energy and distributed energy resources (DER) gained momentum as intelligent ways to sustain resources, minimize environmental impacts, and reduce dependence on imported petroleum. For a variety of economic and institutional reasons, none of these technology areas have yet realized their full technical and economic promise. These technologies were excellent ideas 30 years ago, and they are still excellent ideas now. In at least one future scenario (e.g., the “Double Whammy” scenario), they will be particularly beneficial.

But in all cases, these technology areas represent an enormous opportunity to meet power generation and power delivery needs in efficient, environmentally-sensitive, and sustainable ways. Only a significant, sustained technology R&D program in these areas will bring them to fruition. Key R&D needs in this area include reducing costs, improving efficiency, resolving interconnection issues, and capitalizing on integration opportunities.

Renewable resources pose a range of challenges. For example, the intermittency of wind complicates reliance on wind power. Integration of wind generation with energy storage can help address this issue. Advanced wind forecasting capabilities are also 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.

Distributed energy resources (DER) cut across a broad range of issues in the electric power industry. This increases their strategic value immensely. DER can be a link between power generation and end use, while relieving the need to enhance the high voltage power delivery system. Plug-in hybrid electric vehicles are essentially a mobile DER technology, and small renewables resources, such as photovoltaic arrays or small wind generators, are also DER technologies. Distributed resources are an important element in both alternating current (AC) microgrids and hybrid microgrid systems, which may also include direct current (DC) systems. Looking more long-term, DER is a key part of an envisioned hydrogen-electric economy.

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 (e.g. power generation, power delivery, and end use). Energy storage plants “save” energy for later use, which can avoid or delay the construction and operation of new power generation. Large-scale energy storage improves overall power delivery system efficiency and asset utilization by using off-peak power for on-peak needs and by mitigating transmission congestion. Energy storage can also provide system regulation and spinning reserves. 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 (see Figure 1-3).

In most cases, electric energy storage increases the value of the technologies it complements. For example, storage enhances the effectiveness of power electronics devices; improves the value of renewables by addressing issues of intermittent generation, enhances DER cost effectiveness, and 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.

For these reasons, the 2003 EPRI/U.S. Department of Energy (DOE) "Handbook of Electricity Storage for Transmission and Distribution Applications" (EPRI report number 1001834) states that energy storage devices "may be the most important element of power systems in the future." Further R&D and deployment of electric energy storage technologies is highly likely to be a "win-win" proposition for all involved stakeholders.

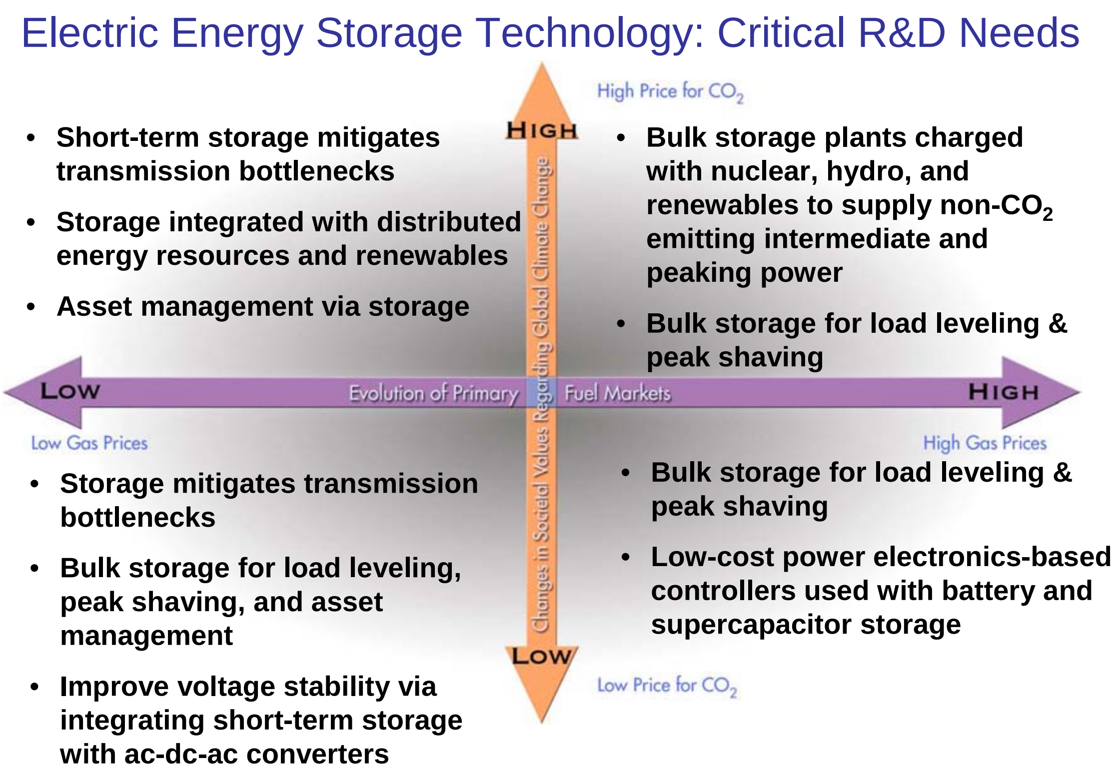

Figure 1-3
Critical technology R&D needs in the energy storage area vary across the scenarios.

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.

Environment

Climate Change, Carbon Capture and Sequestration Technologies

Perhaps even more important than the first three uncertainties identified earlier is the fourth one listed (see page 1-6): uncertainties related to climate change, carbon capture and sequestration technologies. If the climate change issue is perceived to be real, significant technology development is needed to develop and demonstrate technologies to capture and sequester CO_2 at power generation facilities in the U.S. In contrast to many other technology areas that have been addressed over moderate or long periods of time, carbon capture and sequestration technologies are in relative infancy. This major challenge calls for immediate and significant R&D resources. For even in the event of sustained conditions that reflect the "Digging in our Heels" or "Supply to the Rescue" scenarios, many analysts today believe that progression to a carbon-constrained scenario is merely a matter of time.

Placing this issue in a larger perspective, stabilizing atmospheric greenhouse gas concentrations may be one of the grand challenges of the 21st century, in any industry, not just the electric power industry. The overall costs of CO_2 stabilization have been estimated to be on the order of trillions of dollars, depending on the ultimate CO_2 concentration ceiling and the details of implementation. Yet failing to stabilize these concentrations may lead to equal or much larger impacts on agriculture, coastal property, timber, water resources, ecosystems, and human health. Critical R&D needs in this area include the following:

- Determine capacity, effectiveness, human health, and environmental impacts of CO_2 sequestration options
- Reduce cost and/or develop cost effective alternatives to monoethanol amine CO_2 capture
- Significantly improve CO_2 capture in integrated gasification combined cycle and advanced fossil plants
- Explore advanced concepts for carbon capture (non-generation)
- Demonstrate CO_2 capture, transport, and sequestration in pilot plants and full-scale facilities
- Develop tools that enable economic evaluation of various sequestration options

Given the enormous stakes – and the substantial uncertainties associated with climate change predictions, implementation issues, and accompanying impacts – another critical need is to provide policymakers with crucial information to help make environmentally effective and economically efficient climate policy decisions. Stakeholders also need to develop technology policy and establish institutions that encourage and provide incentives for the timely development of technologies to address climate change. Effectively informing stakeholders of the status of technology development in this area is also a critical R&D need.

Challenges and Opportunities: Impacts of Emerging Technologies

Regardless of the technology mix that is addressed, history has shown that one constant remains: potential environmental and human health impacts will need to be addressed. Today, one existing challenge is to achieve near zero emissions (i.e., near zero emissions of NO_x, SO_x, particulate matter, and mercury) from fossil power plants. An already envisioned challenge is the need to provide policymakers with information to make informed global climate policy decisions. In addition, *unanticipated* environmental and human health impacts must also be addressed. For example, distributed energy resource technologies may cause unacceptable local noise or air pollution impacts. Integrated gasification combined-cycle plants may result in byproduct effluent streams with unanticipated impacts. Carbon storage may pose unanticipated ecological and human health hazards. New types of transmission and distribution equipment may emit stronger or different types of magnetic fields than envisioned. Other new generation technologies may pose potential impacts on land use, and water quality and availability. Figure 1-4 shows critical technology R&D areas that address environmental issues for each of the four scenarios examined, and Table 1-2 lists the timing of critical R&D needs in the environment area.

Environmental Science and Technology: Critical R&D Needs

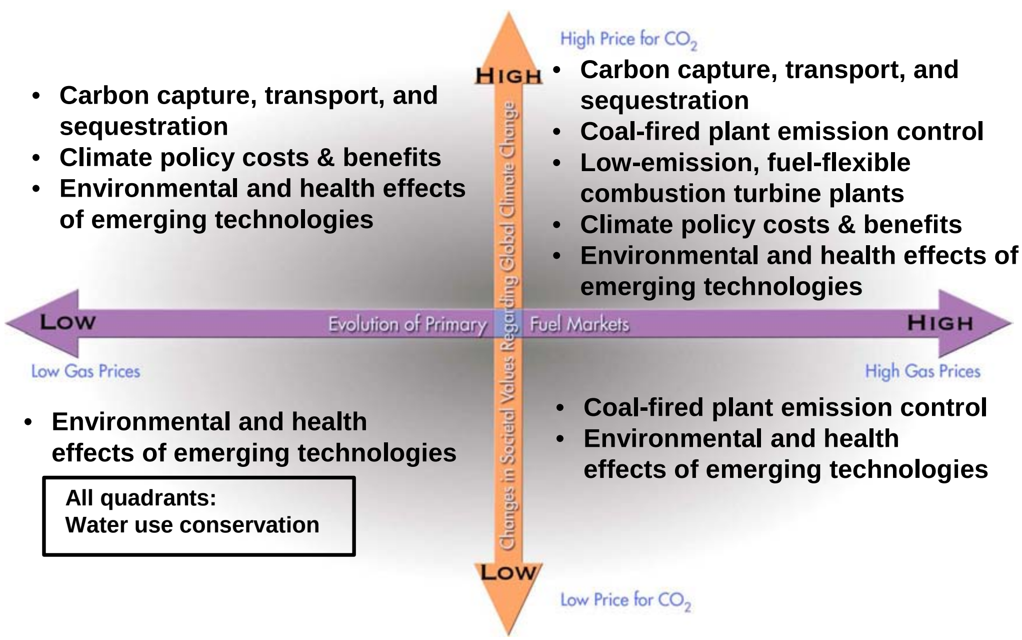

Figure 1-4
Critical technology R&D needs in the environment area vary across the scenarios.

For the upper right and upper left quadrant scenarios, carbon capture, transport, and sequestration R&D is critical. For the lower right and lower left quadrant scenarios, environmental and health effects R&D of emerging technologies is critical.

Table 1-2
Timeline of Critical R&D Needs for the Environment Area

Critical R&D Needs: Environment	Near Term: 1 - 5 Yrs	Mid Term: 6 -10 Yrs	Long Term: 11 - 20 Yrs
Develop and demonstrate a portfolio of cost-effective **carbon capture** technologies	Laboratory demonstration	Pilot plant testing	Commercial-scale deployment
Develop and demonstrate safe, reliable, cost-effective **carbon transportation** methods	Lower-cost commercial-scale systems	Commercial implementation of lower cost systems	Commercial implementation of lower cost systems
Develop and demonstrate reliable, safe, low-cost **carbon sequestration** options	Demonstrate technical viability	Initial field demonstrations	Verify long-term sequestration integrity
Develop and demonstrate **near-zero emissions** from coal-fired power plants	Pilot-scale demonstrations	Initial field demonstrations	Wide scale deployment
Develop means to examine **global climate policy** implementation issues, predict impacts of climate change, assess technology options, and evaluate investment alternatives; the goal is to enable environmentally effective and economically efficient climate policy and technology deployment decisions	Development and evaluation of preliminary global climate policy tools and methods and application of initial policy tools	Refinement of global climate methods and initial application of methods to critical decision making	Ongoing evaluations of policy tools and refinement of methods based on updated global climate change measurements
Develop and demonstrate a portfolio of cost-effective **water use conservation** technologies	Design and laboratory demonstrations	Pilot plant testing	Commercial-scale deployment
Assess potential **environmental and human health impacts** of emerging power generation, delivery, and end-use technologies	Ongoing assessment and evaluation of emerging power generation, delivery, and end-use technologies		

The Power Delivery R&D Challenge

Another key challenge with a range of technology R&D needs is delivering reliable, high quality, secure power. Figure 1-5 shows critical power delivery areas (and corresponding end-use related areas) for each of the four scenarios examined; and Table 1-3 lists the timing of critical R&D needs in the power delivery area.

Power Delivery and End Use Technology: Critical R&D Needs

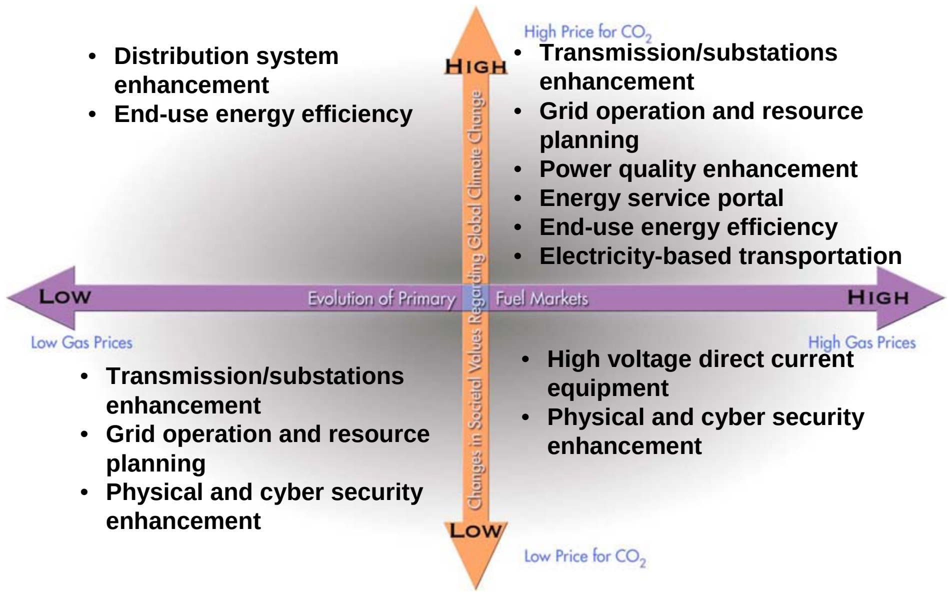

Figure 1-5
Critical technology R&D needs in the power delivery and end-use areas vary across the scenarios.

Movement up or left from the scenario in the lower right quadrant ("Digging in our Heels") dramatically increases power delivery R&D needs. Also, for the upper right quadrant, R&D in electricity-based transportation and end-use energy efficiency becomes more critical.

The wide area power outage in the western U.S. in 1996 and the August 2003 wide area outage in the eastern U.S. and Canada shows that no major power delivery region is immune to massive electric supply collapse. Blackouts of this magnitude incur costs in the tens of billions of dollars – on the same order of magnitude as a major natural disaster such as a severe hurricane or earthquake. The difference is that these outages – or at least the likelihood of their occurrence – can be significantly reduced via a combination of technological advances, operational procedures and institutional changes in the electricity infrastructure. In addition to these wide area regional blackouts, local outages also pose significant economic and social disruption – and they occur much more often than a wide area, regional blackout.

Table 1-3
Timeline of Critical R&D Needs for the Power Delivery Area

Critical R&D Needs: Power Delivery	Near Term: 1 - 5 Yrs	Mid Term: 6 - 10 Yrs	Long Term: 11 - 20 Yrs
Enhance diagnostics, maintenance, and life extension of aging **transmission and substation** assets	Develop and demonstrate advanced transmission and substation asset management technologies	Wide-scale deployment	Evaluate and update new transmission and substation technologies and methods
Develop high-current, high-temperature overhead **transmission conductors**; low-cost, efficient **solid-state switches**	Develop and demonstrate advanced conductors/devices	Wide-scale deployment	Ongoing improvement
Develop cost-effective, integrated, inter-regional **resource planning tools**	Develop models and visualization tools, gather information to demonstrate "holistic planning"	Refine tools and techniques to ensure widespread adoption of holistic planning	Evaluate and update resource planning methods to address evolving uncertainties
Develop and demonstrate "**self healing grid**" components and control systems	Expand existing wide area monitoring and control demonstrations	Integrated pilot-scale demonstration of self-healing grid	Large-scale deployment and evaluation of self-healing grid technologies
Develop/demonstrate fully controllable and flexible **distribution system**, including advanced distribution topologies, communication systems, electrical equipment, sensors and monitoring, and protection and control systems	Field evaluation of pilot components of advanced automated distribution systems	Field integration of components/systems of advanced distribution automation	Large-scale deployment, monitoring and evaluation of advanced distribution automation systems
Develop and demonstrate advances that enable utility providers to offer a menu of "grades" of power, strengthen the distribution system to enable delivery of these grades of **power quality**, and enable manufacturers to design and cost-effectively deploy end-use devices that meet the specifications of these grades of power.	Establish standards for grades of power (including direct current); design monitoring systems; design automated communication & control systems, and verify economic value proposition	Deploy network of monitoring equipment to ensure adherence to power quality standards; deploy distribution automation communication/control	Evaluate and refine power quality systems integrated with distribution automation systems and deploy them at wider scale
Implement measures to **protect the power system** from physical or cyber attacks: conduct vulnerability assessments; develop rapidly deployable recovery transformers and other critical long lead time equipment; cyber harden control/communications systems; develop new cyber security tools; perform security red teaming; perform electric infrastructure interdependency analyses; and develop protective measures (with other infrastructures)	Initial deployments, assessments, and development of new tools	Wider-scale deployment of protective measures; evaluation of measures; and physical and cyber security training	Ongoing assessment and deployment of new tools due to the constant evolution of level and extent of physical and cyber threats

At the same time, a more insidious impact on economic productivity occurs when end uses of electricity are not consistently provided with the high quality power they need. At least 10 percent of total electric load in the U.S. requires digital quality power that is free of transients, harmonics, and voltage surges and sags; and this number is expected to rise to about 30 percent by 2020. Failing to provide this high quality power disrupts digitally-controlled assembly lines, causes errors in sensitive data streams, leads to outages in communication-based industries, and causes other consumer-based impacts with severe economic consequences. Key technology R&D areas to maintain the grid's reliability and integrity include development of advanced power electronics-based controllers, high-current, high-temperature overhead transmission conductors, high voltage direct current (HVDC) lines, a self-healing IntelliGrid, integrated inter-regional resource planning methods, wide area monitoring and control systems, advanced distribution automation, and power quality solutions on both sides of the consumer meter.

While outages due to inadequate power system reliability or quality are relatively rare events, power system disruptions due to intentional physical or cyber sabotage has not yet occurred on a wide scale. Yet, failure to thoroughly address security-related vulnerabilities raises the finite, although small, possibility of a blackout that could dwarf failures due to reliability or quality in scope, longevity, and economic impact. Conversely, reducing or eliminating these vulnerabilities helps ensure the continued operation of the electric power infrastructure, which in turn supplies and enables other critical infrastructures. Key technology R&D areas to maintain power system physical/cyber security include developing rapidly deployable recovery transformers and other long lead time equipment, developing enhanced protection of control systems, conducting vulnerability assessments, and assessing gas-electric and telecommunication-electric infrastructure interdependencies.

The Significant Opportunity at the End Use

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.

Reducing end-use energy consumption via new equipment or upgrades to existing equipment that increase efficiency has long been recognized as an excellent "resource" that offsets the need for new power generation and delivery capacity, while reducing environmental impacts. In fact, there are a host of compelling reasons for developing and deploying end-use energy efficiency technologies. 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.**

At the same time, energy-efficient technologies can help industrial consumers increase productivity and profitability. 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 is also 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.**

Prime 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, lighting alone consumes 20 to 25 percent of all electric energy. Opportunities for savings in the industrial sector are also significant.

Another class of end-use technologies, electric drive vehicles, is a family of vehicles that include any type of automotive transportation that relies all or in part on electric power for propulsion. Electric drive vehicles present an environmentally-friendly, fuel-efficient alternative to conventional vehicles that can help foster independence from the uncertainties of foreign oil. By supporting R&D to speed the technologies needed to commercialize electric drive vehicles, the power industry will provide a valuable national service while realizing an enormous opportunity to develop a new sustainable market. Critical R&D needs in this area include development and demonstration of the next generation of electric drive vehicles.

A technology related to the end-use area that is promising but has yet to be realized is the energy service portal – the electric consumer's window on the world for not only electric services, but a range of other services as well (including value-added home management, information, and entertainment services). The energy service portal empowers consumers by enabling them to make intelligent decisions about energy consumption. The portal can enable a wide variety of demand response programs, applications for integrated building energy systems, energy use monitoring, and automation that is difficult or impossible today. 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.

While some recent experiences with portals has been positive (e.g., two-way metering in Italy and plans at Electricité de France), lack of a standardized open communications architecture and compatibility with a range of applications has precluded widespread realization and deployment of this technology. Clearly, a successfully implemented energy service portal offers benefits to consumers, utilities, and society.

Table 1-4 summarizes R&D needs in the end-use area.

Table 1-4
Timeline of Critical R&D Needs for End Uses of Electricity

Critical R&D Needs: Electricity End Uses	Near Term: 1 - 5 Yrs	Mid Term: 6 -10 Yrs	Long Term: 11 - 20 Yrs
Improve **end-use efficiency** and application-specific benefits for an array of advanced lighting, electrotechnologies, and heating, ventilating and air conditioning technologies; integrate demand response technologies and direct load management strategies and systems	Develop new end-use technologies (e.g., for application to increased efficiency in industrial/commercial equipment)	Demonstrate new end-use technologies (e.g., for application to increased efficiency in industrial/commercial equipment)	Monitor and evaluate deployment efforts of new end-use technologies (e.g., for application to increased efficiency in industrial/commercial equipment)
Develop and demonstrate next generation of **electric-drive vehicles**, including plug-in hybrid electric vehicles, battery-electric vehicles, and fuel cell vehicles (hydrogen fueled) via advances in batteries, vehicle controls, mechanical systems, power electronics, and charging systems	Initial deployment, evaluation, and refinement of plug-in hybrid electric vehicles and battery-electric vehicles	Wide-scale deployment of plug-in hybrid electric vehicles and battery-electric vehicles; initial deployment of fuel cell vehicles	Wide-scale deployment of a range of electric-drive vehicles
Develop and demonstrate low-cost **energy service portal** that employs standardized open communication architecture, ensures interoperability of broad array of consumer services, and works seamlessly with demand response and building/community-integrated energy systems	Initial field deployment, testing, and evaluation of energy service portal	Wider-scale deployment, evaluation, and refinement of energy service portal	Ubiquitous availability and use of the energy service portal; monitor/evaluate broad array of new consumer services

Movement Between Scenarios

The California power market crises in 2000 and 2001 clearly demonstrated the potentially enormous economic, political, and social impacts of tinkering with the 100+ year old electric power industry structure, without careful advanced analysis. The high costs of electricity that resulted from the flawed California market structure cost consumers tens of billions of dollars. The technical field of power market design, once the province solely of economists and college professors, is now practiced worldwide in the restructuring and privatizing of power industries. The decisions made in the next 10-20 years as to the appropriate mix of regulation and market mechanisms in the U.S. electric power market will affect not only wholesale and retail power prices, but the decisions will also affect whether needed investments in transmission and generation assets will occur in a timely manner to ensure continued grid reliability.

One conclusion of this report is that an important part of scenario analysis is not only an examination of the likely R&D needs in each scenario, but the critical impacts when moving *between* scenarios (see Figure 1-6). For example, price volatility in power markets or fuel markets can lead to general trends that force the utility industry to move from one scenario condition to another over a relatively short period of time. A wide range of factors can affect the future price of natural gas, including gas availability and maturation of the liquefied natural gas market. Similarly, various factors can change the price of CO_2 emissions specifically and the value placed on environmental protection more generally. These include a change in political decision makers, changes in emphasis of global climate accords, changes to domestic environmental regulations or adoption of new ones, and emergence of new scientific evidence regarding human health effects and emissions.

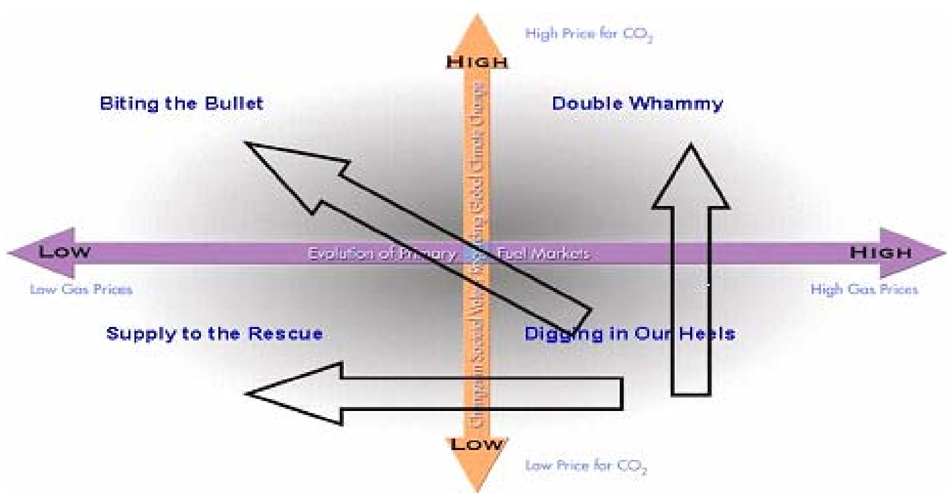

Figure 1-6
R&D needs should be aligned with specific “what if” scenarios and account for potential movement from one scenario quadrant to another (e.g., caused by expected price volatility of premium fuels)

At the same time, an understanding of the stability of the various factors and drivers within any scenario is important. For example, will these conditions endure long enough to mount and require a new technology path? Alternatively, will conditions remain stable for a short enough period of time so they are essentially self-correcting?

This points out the need to be able to predict the impacts of these changes. A key R&D need in this area is the capability to simulate and model a broad range of power market rules, conditions, and strategies *prior to* implementation in the real world. Equally important is the need to understand the underlying price dynamics and limiting physical factors that will bound prices, such as the mechanisms and economic triggers for substituting natural gas-fired combined cycle generation for coal generation. This complex and dynamic phenomenon is vital to understanding price floors for natural gas when prices decline – for different regulatory rules and time periods.

Related implications of each scenario are financial impacts on customers. The amount of money available for R&D, technology investments and demonstrations, as well as power and transmission infrastructure maintenance, upgrading and replacement, is likely to be approved by the local regulatory entity (e.g., the state public utility commission). Thus, it is important to understand how a business environment of rising rates (often related to high fuel costs) or a legacy of high rates in a region, may constrain the flexibility to achieve desired investments across the range of both environmental and reliability-driven technologies. Alternatively, decreasing costs may create opportunities to develop and install new technologies. The challenge is to bring technologies to a point of commercial readiness to allow the gradual makeover and improvement of the electric infrastructure.

A related and daunting challenge is to consider and evaluate how developments outside the power sector also may constrain investment flexibility within the power sector. The high price of oil has an important “income effect” on consumers and can align with and heighten inflation; rising oil prices tend to increase natural gas prices used to fuel combustion turbine power plants, which increases electricity prices. By addressing these developments, social and financial recovery of investments can occur when they are most needed.

Movement between scenarios is a time period when change and risk are greatest, which can paralyze investment due to heightened uncertainty. Capital investment in advanced coal technology, for example, may appear to violate least-cost principles at times when natural gas prices fluctuate downward. Increasing awareness of the fact that diverse methods are needed to respond to change is an ongoing challenge. A summary of the timing of critical R&D needs in the area of power and fuel markets is presented in Table 1-5.

Table 1-5
Timeline of Critical R&D Needs for the Power and Fuel Markets Area

Critical R&D Needs: **Power and Fuel Markets**	**Near Term:** **1 - 5 Yrs**	**Mid Term:** **6 - 10 Yrs**	**Long Term:** **11 - 20 Yrs**
Determine, model, and assess appropriate balance of regulation and **power market** mechanisms (e.g., in areas of financial risk management, market power, investment planning, and fuel markets) to achieve effective long-term generation and delivery of power.	Model and evaluate alternative mechanisms to meet needs of power system stakeholders	Inform market restructuring efforts at Federal, regional, and State levels; refine methods and assessment tools	Ongoing review of restructuring efforts worldwide, refinement of methods, and cooperation with government and private agencies to evaluate/update restructured market policies and regulations
Develop and implement advanced **power market** simulation and modeling tools	Ongoing model enhancement and evaluation of proposed market redesigns or rule changes		
Develop innovative ways to minimize cost of capital for **power market** participants by creation of new financial arrangements; and develop mechanisms for efficient coordinated investments in generation and transmission	Ongoing development and refinement of power market mechanisms		

Technology Innovation and Emerging Technologies

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 course of 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, materials science, environmental science, and computer science – have also changed our lives in fundamental ways. These advances share the 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.

EPRI has identified six “innovation” technology areas with a robust potential for dramatic improvements in the electric power industry (see Figure 1-7 and Table 1-6):

- **Biotechnology:** Better understanding of basic biological processes and mechanisms; genomic research that identifies the best available genetic improvements to microorganisms; light harvesting techniques that mimic photosynthesis; research into ion transport in plants; biofilms that protect against corrosion; and development of improved enzymes and improved catalysts.

- **Smart materials:** Effective integration of discrete smart-system sensors, actuators, and processors; miniaturization of smart components to allow embedding in structures; wireless communication with embedded components; real-time condition assessment of critical components; and control of power plant chemistry and minimization of undesirable combustion products.

Technology Innovation/Emerging Technologies: Critical R&D Needs

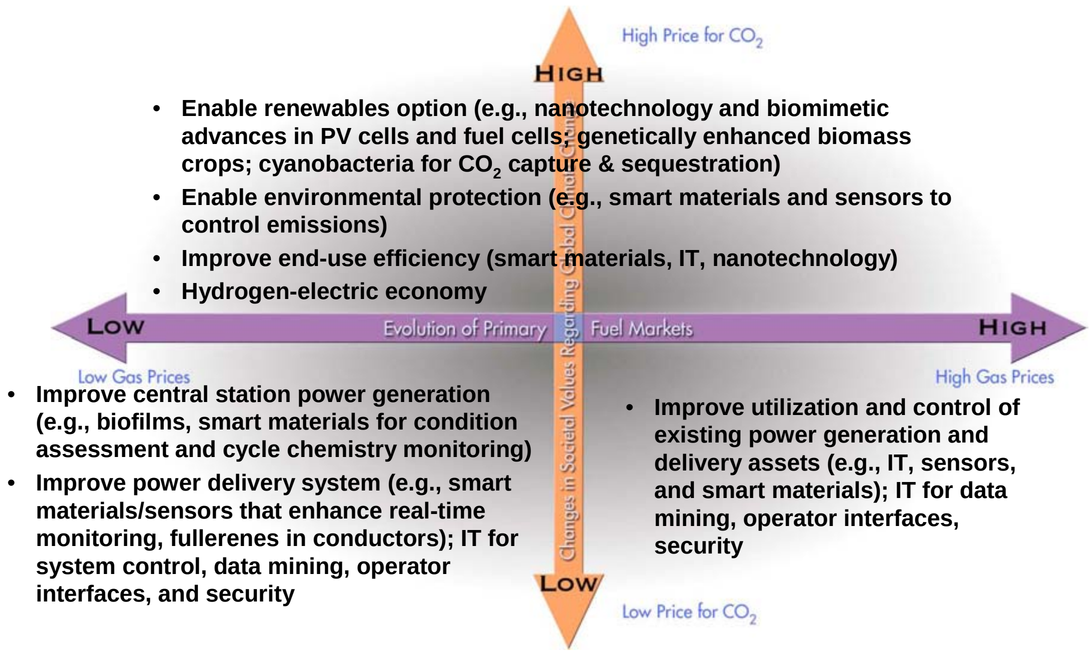

Figure 1-7
Breakthroughs in specific innovation technology areas will help meet challenges in each scenario

Table 1-6
Timeline of Critical R&D Needs for the Technology Innovation/Emerging Technology Area

Critical R&D Needs: Technology Innovation	Near Term: 1 - 5 Yrs	Mid Term: 6 - 10 Yrs	Long Term: 11 - 20 Yrs
Develop **nanotechnology** for application to photovoltaics, energy storage, thermoelectrics, sensors and networks, structural materials, fuel cells, and catalysis	Exploratory, laboratory-scale efforts, and proof-of-concept studies, including: • High dielectric nano materials and supercapacitors • Biomimetic materials • Distributed computing systems	Pilot-scale demonstrations of promising applications, including: • High dielectric nano materials and supercapacitors • Biomimetic materials • Distributed computing systems	First commercial demonstrations of viable, cost-effective applications, including: • High dielectric nano materials and supercapacitors • Biomimetic materials • Distributed computing systems
Additional areas of potential high value include **biotechnology, smart materials, information technology, sensors,** and the **hydrogen-electric economy**			

- **Nanotechnology:** Development of nanoscale fabrication processes; high-strength bonds with matrix substances; advanced self-assembly techniques; greater understanding of quantum effects; communication links with nanoscale structures; cost reductions in photovoltaic (PV) materials; improvement in thermoelectric devices for electronic cooling and power generation; development of a new class of supercapacitors and high dielectric insulation materials; sensors for use in self-diagnosing, self-healing components and systems; improved structural materials/fullerenes; and higher performance fuel cells.
- **Information technology (IT):** Advancements in neural networks, fuzzy logic, genetic algorithms, distributed computing systems, intelligent agents, and artificial intelligence; monitoring and control of complex dynamic infrastructure systems; enhanced data mining; improved man-machine interfaces; and increased security and privacy.
- **Sensors:** Development of acoustic wave detectors and electrochemical microsensors; increased temperature resistance of optical sensors, sensor housings, claddings, coatings, and adhesives; development of low-cost, versatile fiber Bragg gratings; microminiaturization of sensor components to sense chemical species in emissions and waste streams; distributed sensing of voltage, current, and temperature; and control of the electrochemistry of power plant circulating water.
- **Hydrogen-electric economy:** Development of low cost, safe, and efficient methods of compressing and storing hydrogen; achieve breakthroughs in reducing the cost of hydrogen production; and develop low-cost capability for long-distance piping of high-pressure hydrogen.

Application of the Information in This Report

Audiences for this report include internal R&D 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. 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.

Utilities and other organizations will also be able to utilize and leverage the information in this report. 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, regulatory rate caps, 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 are also useful as input into utility company analyses that address these issues. Several items may help support these company analyses, including the following:

- If a company has developed its own set of scenarios or roadmap, then the scenarios and roadmap in this report can serve as a point of comparison to determine if any key factors or considerations are consistent or overlooked.
- 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.
- Each scenario presents a different context in which to test the success of a companies' current strategy and competitive actions.

Technology R&D Target Areas

Volume 2 of this report contains more information on technology R&D needs, including detailed descriptions of these needs and discussions of their implications in the four scenarios. In Volume 2, these needs are organized into 20 technology R&D target areas, which are apportioned into seven groups, as follows:

- Power generation
  - Coal power generation technologies
  - Natural gas fired generation technologies
  - Existing nuclear power
  - Future nuclear power capabilities
  - Renewable resources
  - Distributed energy resource
- Electric energy storage
- Environment
  - Carbon capture, transport, and sequestration
  - Emissions reduction and control
  - Environmental science and technology
- Power delivery
  - Transmission and substations
  - Grid operations and resource planning
  - Distribution systems
  - Power quality
  - Physical and cyber security

- End uses of electricity
  - Energy service portal
  - End-use energy efficiency
  - Electricity-based transportation
- Power and fuel markets
- Technology innovation and emerging technologies

Priority 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. 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. Hence, each Committee member cast a total of 20 votes. In effect, they could choose only 20 of the top 100 R&D needs.

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. Appendix A contains the detailed results of this rating process.

In the power generation group (see Table A-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 votes 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 [of future nuclear power] (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 [existing nuclear] plant reliability and efficiency (e.g., by reducing materials degradation and improving fuel reliability) (5)

In the power delivery group (see Table A-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 votes 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 A-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 votes 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 A-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 votes 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)

Recommendations and Next Steps

This report lays the foundation for significant further work. Presented below are the recommended next steps, which are divided into two categories.

Implementing the Findings in This Report

- EPRI will implement the R&D topics and conclusions herein as key input to its 3-year R&D planning process, in each EPRI Technical Sector. The rating results from the EPRI Research Advisory Committee will be used to guide the allocation of EPRI resources to these efforts, by developing action plans to assemble collaborative R&D teams that sponsor and fully address the identified high rated topics.
- EPRI will examine use of the conclusions in this report as a framework to set milestone goals and their timing for each EPRI Sector.
- Utilities can implement, as appropriate, the framework and content of this report to develop individual utility strategic technology R&D plans. EPRI will work with utilities and other stakeholders to facilitate these efforts, as appropriate.
- EPRI will inform government agencies, regulators, associations, consumer groups, equipment manufacturers, and other stakeholders on the framework and content of this report to assist and guide their strategic R&D plans and coordination activities.
- EPRI will update this report periodically, as needed, to reflect new technological advances, regulatory realities, market changes, and economic factors facing the electric power industry.

Further Research Needed

- EPRI will develop 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. These wild cards may include, for example, the occurrence of a series of widespread North American power system blackouts; a major nuclear accident (anywhere in the world); a nanotech breakthrough that enables micro-inverters to be deployed so that microgrids can be implemented with low losses and at low cost; or development of an efficient bulk energy storage technology at one-third the cost of existing storage systems.
- EPRI will develop an R&D strategy for the critical area of human resources in the electric power industry. This will include identifying the challenges the industry faces in this area (e.g., shortage of trained professionals, “lost” knowledge as professionals retire, and lack of public understanding of electricity-related issues), solutions currently being addressed, and solutions that are needed (e.g., improved education, training, human interfaces, and

knowledge capture). The goal is to thoroughly address this overarching issue that cuts across all dimensions of the industry, assemble disparate information on this topic in a single document, and provide new insights and creative ways to address the human resource area.

- EPRI will review and compare the findings of this document with the findings of roadmaps and visionary documents developed by other organizations, including but not limited to the following:
  - The U.S. Department of Energy's "National Transmission Grid Study"
  - The U.S. Department of Energy's "Grid 2030" report
  - The National Rural Electric Cooperative Association's strategic roadmap entitled "Electric Cooperative Technology Solutions"
  - Other organizations with similar documents may include the California Energy Commission, Edison Electric Institute, Gas Technology Institute, National Institute of Standards and Technology, National Laboratories, National Science Foundation, New York State Energy Research and Development Authority, the U.S. Department of Defense, the U.S. Environmental Protection Agency.
- EPRI will identify the roles and responsibilities of key stakeholders in each key R&D area and estimate the costs and timing to carryout the high rated R&D work identified. Stakeholders include utilities; trade associations and professional societies; collaborative R&D organizations; Federal, State, and local government agencies; regulatory agencies; equipment manufacturers and consultants; environmental organizations; and universities.

A
RATING OF R&D NEEDS: RESULTS

Tables A-1 through A-4 document the results of the EPRI Research Advisory Council (RAC) rating process conducted on October 24-26, 2006.

Table A-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 A-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 tools (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 A-3
Rating of R&D Needs: Energy Storage and End-Use Efficiency

19 ELECTRIC ENERGY STORAGE	10 END USE ENERGY EFFICIENCY	16 ENERGY SERVICE PORTAL	11 ELECTRICITY-BASED TRANSPORTATION
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 member

Table A-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 member

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