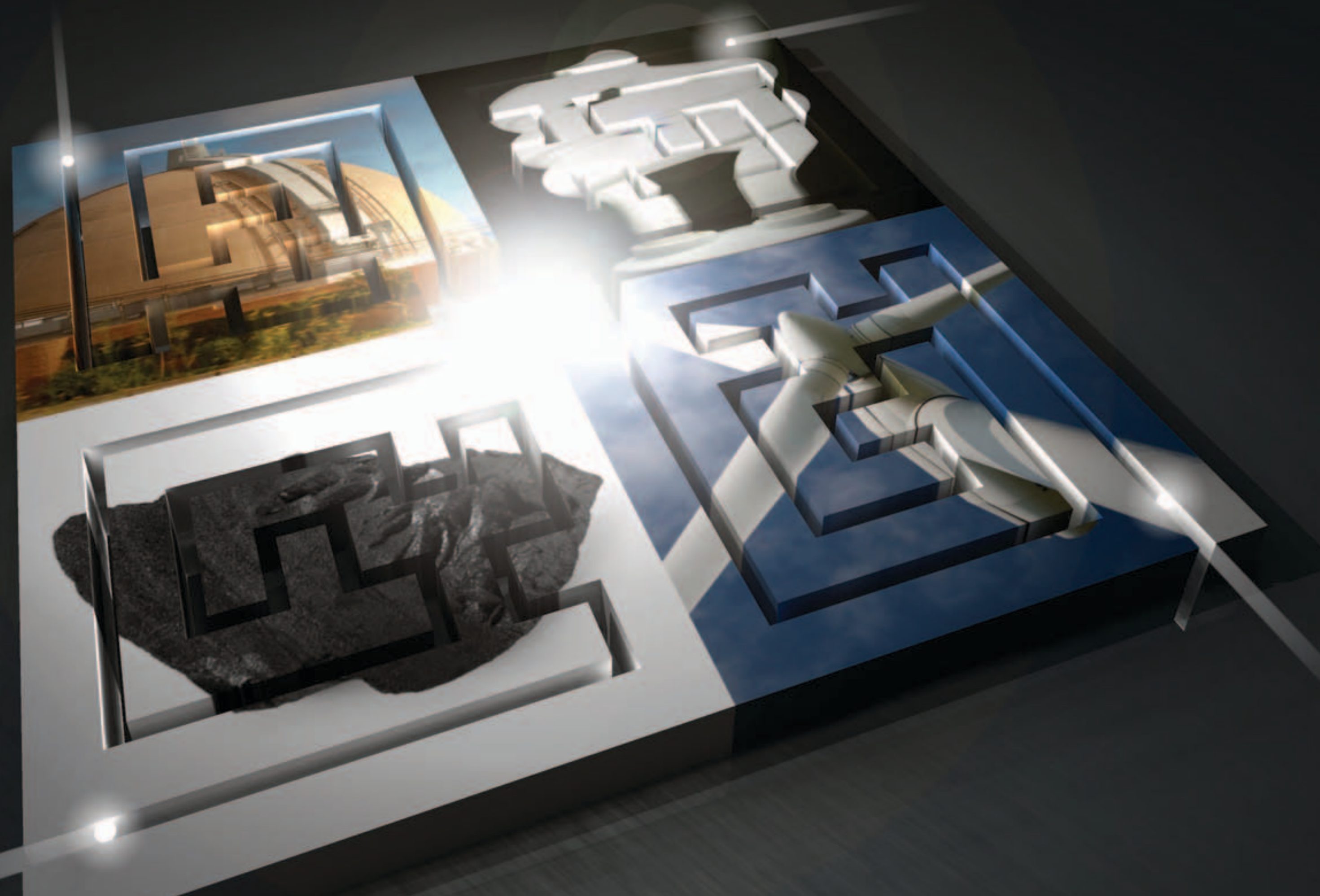
FALL 2007

EPRI JOURNAL

ELECTRIC POWER RESEARCH INSTITUTE

PATHWAYS TO SUSTAINABLE POWER

In a Carbon-Constrained Future



ELECTRIC POWER
RESEARCH INSTITUTE

The Electric Power Research Institute (EPRI) leads research, development, and demonstration of technical and operational solutions in electricity generation, delivery, and use. The focus and application of EPRI's research and activities span virtually every aspect of the power industry, including reliability, safety, the environment, and energy efficiency. The Institute's collaborative model engages EPRI members, participants, scientists, and engineers, along with experts from academia and other business sectors. As an independent, nonprofit center for public-interest energy and environmental research, EPRI's work is supported both by its members, which represent more than 90 percent of the electricity generated in the United States, and by growing international participation, representing more than 15 percent of EPRI's program support.

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EDITORIAL

COVER STORY

EPRI's 2007 Summer Seminar brought together regulatory, industry, academic, and policy leaders to discuss the actions required to begin resolving the climate dilemma. Technical solutions took center stage in the spirited and wide-ranging discussions.

FEATURES

Two groundbreaking analyses, PRISM and MERGE, point to the benefits of developing the Full Portfolio—a technically feasible and affordable combination of advanced technology options.

If the Full Portfolio of technologies becomes the industry's ultimate destination, how do we get there? EPRI has identified four technology pathways to answer that question and serve as the framework for a robust RD&D agenda.

DEPARTMENTS

LISTINGS

Editorial

From Analysis to Action

In this issue of the *EPRI Journal,* we look at a carbon-constrained future through two key EPRI analyses: The PRISM analysis highlights technology advancements essential to decarbonizing the electricity sector; the MERGE analysis illustrates the economic importance of a full portfolio of technologies to meet potential CO_2 emissions reduction targets. To me, one fundamental implication of these analyses is very clear—we must move from analysis to action if we are to deploy this full portfolio of technologies in a timely and effective manner.

What actions must we consider? First, we must work to slow the growth of electricity sector CO_2 emissions by making more-efficient use of the electricity that is already being produced. Many existing technologies, such as compact fluorescent lighting, can deliver near-term improvements in end-use efficiency, and many new technologies are in various stages of development. EPRI's Energy Efficiency Initiative was launched earlier this year and has brought together more than 40 participating companies to develop the next generation of energy efficiency technologies.

Also this year, more than 1400 technical experts from across the electricity sector collaborated through EPRI's program committees and technical advisory councils to identify critical technology gaps and prioritize key research, development, and demonstration programs needed to de-carbonize the electricity sector. This collaboration culminated with a joint meeting of the EPRI Board of Directors and the EPRI Research Advisory Committee in which seven critical technology demonstration projects were selected for detailed evaluation.

Two of the critical projects are key enablers for energy efficiency, renewables, distributed energy resources, and plug-in hybrid electric vehicles. One is the demonstration of a "smart" distribution system making use of plug-and-play standards. The other is a field demonstration of advanced compressed-air energy storage for load shifting and increased penetration of intermittent renewables.

Five of the critical projects are aimed at demonstrating the effectiveness and reducing the cost of carbon capture and storage (CCS) from coal plants. These include two projects for demonstrating different postcombustion CO_2 capture technologies with storage; a project to demonstrate integrated gasification–combined-cycle (IGCC) operation with integrated CCS; a high-efficiency pulverized coal plant with state-of-the-art emission controls and integrated CCS; and demonstration of a key enabling technology to lower the cost of O_2 production for IGCC and oxyfuel plants.

These projects target critical gaps that must be filled to achieve "The Full Portfolio" identified in the PRISM and MERGE analyses. They are designed to complement ongoing private sector and government sector activities; and where there is not a critical gap—there is not a project.

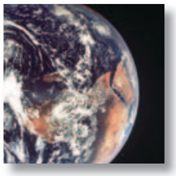
For example, challenges remain in deploying new advanced light water reactors (ALWRs), but these challenges can be addressed through ongoing programs without major demonstration projects. Sufficient private sector investment and competition is in place to advance specific renewable generation technologies, but critical technology gaps exist in the large-scale integration of these resources into the grid.

These seven projects were identified through EPRI's collaborative process, and we expect to participate in each of them; but they are electricity sector projects, not EPRI projects. Each will require a consortium of companies drawing on both private sector and government funding. During the coming months, the EPRI Board of Directors, Research Advisory Committee, and staff will further evaluate and, if appropriate, lead the development of a plan to fund and implement each project.

Together, these seven projects set priorities and provide a framework for action. They move us from debating vague generalities about RD&D funding needs to a focused plan for specific critical technology projects. Not every project may proceed, and others will likely emerge. Ultimately these technologies will require significant lead time and investment to be broadly deployed. And that requires all of us in the electricity sector to stand on common ground and to move toward the common goal of The Full Portfolio. Analysis can help put us on common ground, but only concerted action can move us toward the goal.

SR Specker

Steve Specker
President and Chief Executive Officer



International

Energy developments
around the globe

On-Line Monitoring Improves Instrument Calibration at British Energy

The thousands of instruments that monitor conditions in nuclear power plants must be calibrated periodically to ensure they are accurately measuring pressures, temperatures, and other parameters vital to plant performance and safety. Such instrument calibrations are typically performed during refueling outages—that is, once every 18 to 24 months.

Calibration is both time consuming and costly. Substantial labor is devoted to isolating the instruments, calibrating them, and returning them to service—activities that contribute to outage duration and worker radiation exposure. Moreover, because calibration involves intrusive techniques, human error can sometimes degrade the performance of instruments that had previously been working properly.

Motivated to reduce outage duration and calibration costs at its Sizewell B nuclear generating station, British Energy engaged EPRI to develop and deploy a better approach to calibrating safety-related instruments.

Better Information Means Longer Intervals

The calibration histories of process instruments in nuclear plants show that high-quality instruments can maintain their accuracies longer than an 18- to 24-month fuel cycle and therefore may not need to be calibrated as often as they have been. In the mid-1990s, this finding spurred the nuclear industry and EPRI to explore a promising alternative to time-based calibration: on-line monitoring (OLM) of instrument channels.

Using nonintrusive techniques, OLM evaluates instrument channel performance by assessing consistency with other plant indications, providing more-frequent and more-accurate information about instrument channel conditions than can be gleaned from traditional periodic calibration. Because on-line monitoring techniques capture operational variability effects, they provide a more-accurate assessment of calibration status for the given operating point. As a result, OLM allows calibration to be performed according to an instrument's actual condition rather than on a purely time-based schedule.

Many nuclear plants have applied OLM successfully to general instrumentation, but British Energy's Sizewell B station became the first to apply the EPRI guidelines to extend the calibration interval of safety-related instruments. Software coding for the project was performed by Analysis and Measurement Services Corporation.

Cost Savings at Sizewell

British Energy initially applied the OLM techniques to about 200 instruments at Sizewell B, focusing on the pressure, level, and flow transmitters in the plant's primary and secondary protection systems. Overall, 80% of the transmitters evaluated during the first OLM cycle were found to be within calibration tolerance throughout the fuel cycle. During the first outage, most of the transmitters that were candidates for calibration interval extension (70% of the total transmitters evaluated) were, in fact, extended. The additional 10% of transmitters that were within tolerance were nonetheless scheduled for calibration to maintain conservatism during the initial implementation.

British Energy estimates that OLM, when fully deployed, will routinely reduce outage duration to 20 days from the 25 days normally required for transmitter calibration, saving £1.5 million per avoided outage day, or £7.5 million per operating cycle. Additional savings are expected from reductions in labor costs, radiation exposure, and calibration errors. British Energy's goal is to expand the OLM application to nearly 2500 transmitters, including many in the secondary system (steam side) of the plant.

The project methodology and application for the Sizewell project, together with a set of supporting analyses and results, are published in the EPRI report *Plant Application of On-Line Monitoring for Calibration Interval Extension of Safety-Related Instruments: Volumes 1 and 2* (1013486).

For more information, contact Joseph Naser, jnaser@epri.com, 650.855.2107.

2007 Summer Seminar

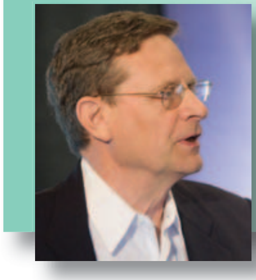
Electricity Solutions
Carbon-Constrain

The Story in Brief

A successful response to the threat of climate change will require substantial technical work as well as practical problem solving in the political, regulatory, and public arenas. EPRI's 2007 Summer Seminar brought together regulatory, industry, academic, and policy leaders to discuss critical issues and delineate the initiating actions required to begin resolving the climate dilemma. Although the global nature of climate change amplifies its complexity and uncertainty, technology must play a leading role in winnowing opportunity from challenge and crafting a viable solution.

Climate change has a decidedly dual personality. On the one hand, the scope and scale of the challenge can seem insurmountable. On the other hand, climate change enthusiastically invites innovation, through the liberal development and application of environmentally friendly technologies across the economic landscape. At the 2007 EPRI Summer Seminar in August, presenters and participants vividly reflected both personalities, linking climate change challenge to climate change opportunity in the context of a full portfolio of electricity sector technologies.

> “Whether it’s through a cap-and-trade system, a carbon tax, or some other mechanism, no private actor is going to do anything unless the effective price of carbon dioxide is $35 per ton or greater.”
>
> Granger Morgan, Carnegie Mellon University



For more than 30 years, the EPRI Summer Seminar has assembled a diverse mix of executives, policymakers, and leaders from industry, academia, government, and non-governmental organizations to discuss critical issues impacting the electric utility sector. The theme for the 2007 Summer Seminar—Electricity Solutions for a Carbon-Constrained Future—reflected the elevated status climate change now occupies in business, scientific, and policy circles. While the participants candidly addressed the challenges facing the electricity sector, they confidently endorsed a critical and expanding role for technology. Dynamic interaction between presenters and the audience sharpened the debate and highlighted unique perspectives.

Bathtubs and Bullet Trains

The greenhouse gases that contribute to global warming, including carbon dioxide (CO_2), aren’t like conventional pollutants. “Conventional pollutants like sulfur dioxide or nitrogen oxides have a residence time in the atmosphere of just a few hours or days,” said M. Granger Morgan, chair of EPRI’s advisory council and head of Carnegie Mellon University’s Department of Engineering and Public Policy. “If I stabilize emissions, concentrations promptly stabilize. Carbon dioxide isn’t like that. If I stabilize emissions, concentrations continue to grow because at least some carbon dioxide remains in the atmosphere for more than 100 years.”

In welcoming participants to the Summer Seminar, Morgan likened the climate change challenge to a bathtub with a big faucet and a small drain, where the level of water in the tub represents the atmospheric concentration of CO_2. To reduce CO_2 levels, flow from the faucet must slow to the point where the drain can catch up. In a world where economic growth is largely powered by industrialization and where billions of people are striving to increase their standard of living, stemming this flow represents a daunting and long-term task.

Jeff Sterba, chairman of EPRI and chairman, president, and CEO of PNM Resources, painted a different picture to convey the urgency associated with climate change action: “I think of carbon buildup in terms of a train pulling out of the station going 3 to 5 miles an hour. When it’s going that speed, it’s fairly easy to slow it, stop it, and start to push it backward. When it’s going 20 or 30 miles an hour, it’s a bit harder to stop. You’re going to hear squealing of brakes, a lot of whining motors—maybe see some minor damage. But if it’s going 100 miles an hour, it’s going to do lots of damage before you can bring it to a stop and start to push it back. That’s the inertia that we have to work against, and the longer we take to debate what has to be done as opposed to acting on what has to be done, the faster that train will be.”

The bathtub and bullet train analogies are particularly apt in the context of global climate change because both lend themselves to technological solutions: design a bigger drain, close off the tap, engineer a better set of brakes, etc. “Our role is to provide technology options for society,” said Steve Specker, EPRI president and CEO in his keynote address. “The public can decide, at the local, state, or national level, which technology options they’re going to pursue. We as technologists have to put as many of them out there as possible.”

Specker outlined the PRISM and MERGE analyses that EPRI has conducted to assess the technological and economic feasibility of a full portfolio of options for achieving significant CO_2 emissions reductions in the U.S. electricity sector. The so-called Full Portfolio encompasses energy efficiency, plug-in hybrid electric vehicles, distributed energy resources, renewable energy, nuclear power, advanced coal-fired generation, and carbon capture and storage. The PRISM and MERGE results, which are described in detail in the article on page 14, functioned as a de facto starting point for the discussions during the Summer Seminar.

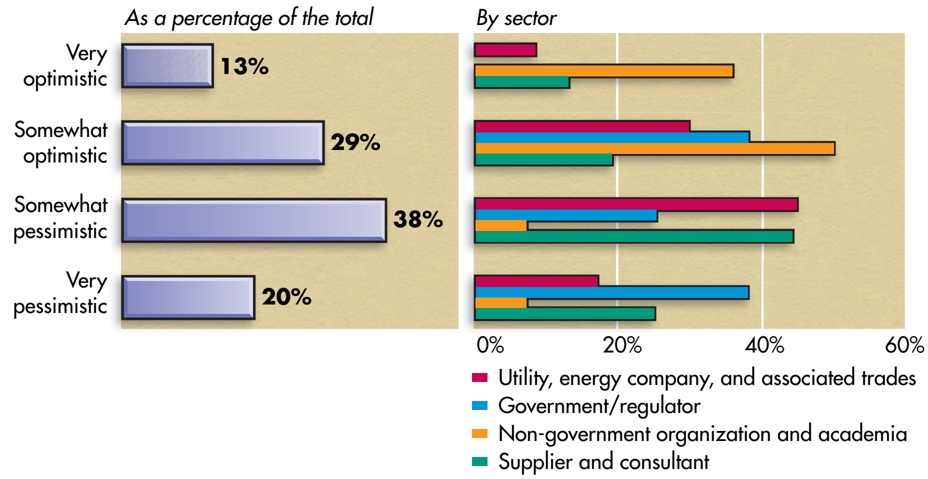
Bigger and Better

The seminar’s opening session, “Development and Deployment Challenges of Achieving CO_2 Reductions: Critical Path Issues,” brought the magnitude of the challenge into sharp relief. The issue of scale looms large over any technology-based strategy to reduce CO_2 emissions, and it has two distinct elements: (1) the degree of technology deployment or reduction of demand growth required to make a significant impact, and (2) the scale-up required to move emissions reduction technologies from research and development through demonstration and commercialization.

With respect to the first element, consider nuclear power. The EPRI PRISM analysis projects 64 GW of new nuclear capacity by 2030 to contribute to significant electricity sector CO$_2$ emissions reductions. "Assuming an average nuclear plant capacity of 1350 MW, getting to the PRISM goal of 24 GW by 2020 will require about 17 new reactors," said Admiral Frank Bowman, president and CEO of the Nuclear Energy Institute. "With 17 companies having signaled their intentions to file applications for new reactors for up to 31 plants, that's feasible. Now, going all the way to 64 GW by 2030, which entails another 30 plants, is a little heavier lift, and it really comes down to how the first 6 are going to go. My view is that reaching the 47 number is doable, but it's going to require a perfect alignment of a number of elements."

Aligning these elements may be difficult, but the audience provided an optimistic counterpoint. In a comment from the floor, attendee Pierre Daurès, associé gérant with Intellact, reminded the participants about France's large-scale commitment to nuclear energy. "While there will be impediments to realizing a large nuclear power plant program, they are not insurmountable. France brought 50 nuclear power plants on-line in less than 25 years."

Question: How optimistic are you that the PRISM CO$_2$ emissions reductions can be met?



The 2007 EPRI Summer Seminar was attended by over a hundred people representing a wide variety of organizations and stakeholder groups. Audience thoughts and opinions were captured regularly during the two days of presentations by an electronic audience response system. This quick polling on key questions stimulated frank comments from attendees and helped focus panel discussions on strategic issues.

Heavy lifting will also be required for renewable energy, advanced coal, and energy efficiency. Replacing all residential incandescent light bulbs in the United States with compact fluorescent bulbs can reduce energy consumption significantly—by about 4%. However, in light of expected electricity demand growth of 40% by 2030, and increased demand associated with electronic loads such as plasma TVs, digital converters, and computers, more may be demanded of energy efficiency, particularly since it represents a near-term emissions reduction option.

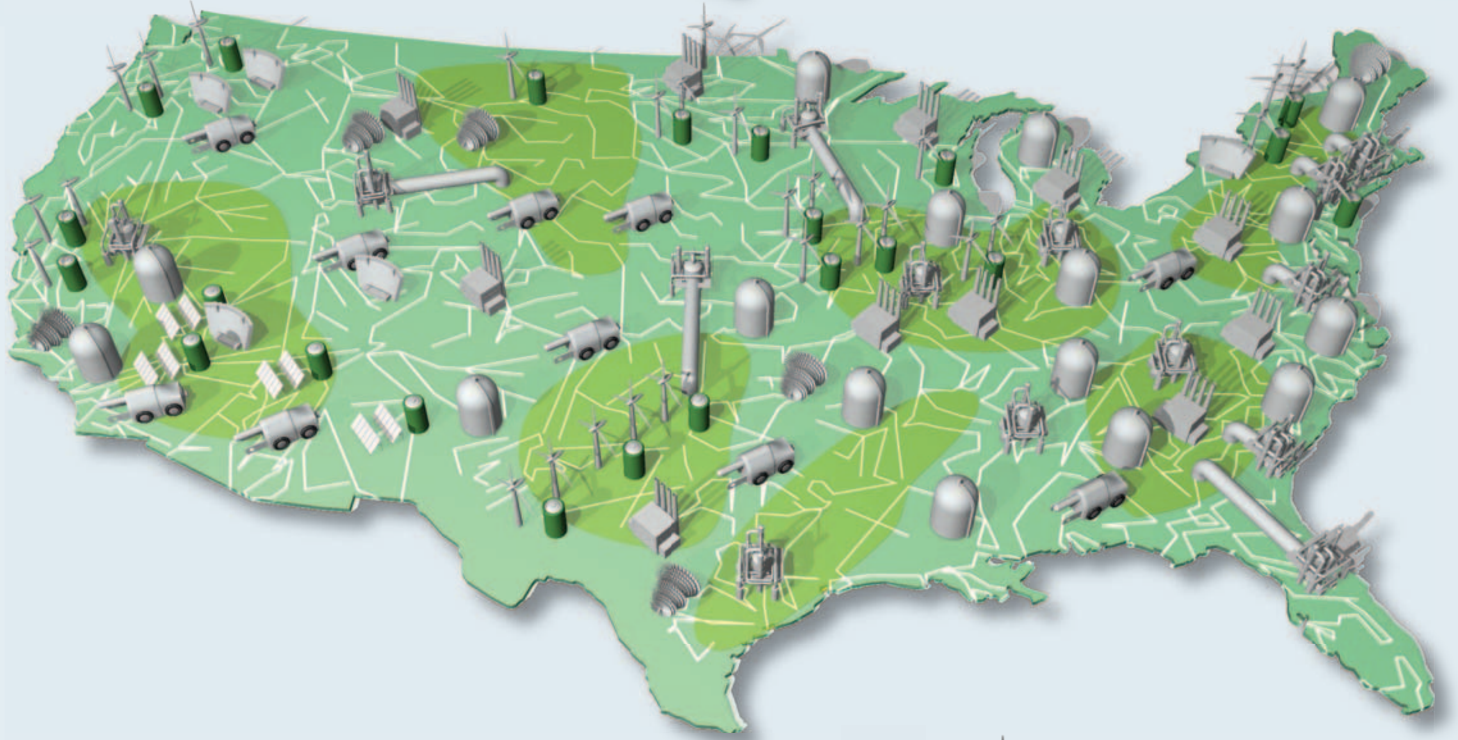
Renewable energy has made significant inroads in commercial penetration, thanks in large part to determined research and development efforts and to generous (if undependable) production tax credits. Wider penetration hinges on mitigating intermittency concerns and integrating renewable resources into the grid. "One of the challenges in developing these resources is that they tend to be transmission-remote," said John Geesman, commissioner of the California Energy Commission. "In California, we expect to derive more than 4000 MW of new wind capacity from the Tehachapi area, but it will cost well in excess of a billion dollars to build the transmission system necessary to harvest that resource."

The second element in the issue of scale—the difficult progression from research to commercialization and deployment—is most clearly demonstrated with respect to carbon capture and storage technology.

The shape of future U.S. power production will depend on what advanced technology is developed and deployed over the next 20 years. EPRI studies compared the likely generation mix for a limited portfolio of technology options with that for a more-robust full portfolio; both scenarios seek to stabilize CO_2 emissions at 2010 levels through 2020 and further reduce them by 3% a year through 2050. The positions of generating facilities are representative and do not indicate the locations of actual plants.

Limited Portfolio

Full Portfolio



Limited Portfolio

R&D focuses primarily on evolutionary improvements in conventional coal- and gas-fired generation, further development of renewable technologies, and increases in end-use efficiency; nuclear capacity remains at existing levels. Carbon capture and storage (CCS) technology is not pursued, and improvements in the transmission and distribution grid are modest.

The Outcome for 2030

While the Limited Portfolio can achieve CO_2 *reduction goals, it will require substantial demand reduction (over a trillion kilowatt-hours a year). Natural gas will replace coal as the dominant generation fuel, leading to significantly higher electricity prices.*

Total Generation

Coal: 1220 TWh
Nuclear: 760 TWh
Gas: 1940 TWh
Hydro and other renewables: 580 TWh

Full Portfolio

In addition to the Limited Portfolio's advances, advanced coal plants that incorporate CCS technology are developed, and a large number of advanced LWR plants are added to the existing nuclear fleet. A "smart" power grid, energy storage technology, and plug-in hybrid vehicles (PHEVs) are also developed and deployed.

The Outcome for 2030

Demand reduction under the Full Portfolio will be substantially less than that for the Limited Portfolio. CCS technology will allow coal use to grow in place of natural gas, drastically reducing electricity price increases. The smart grid and PHEVs will increase end-use efficiency, while storage technologies will allow better integration of intermittent renewables.

Total Generation

Conventional coal: 1120 TWh
Coal with CCS: 1540 TWh
Nuclear: 1440 TWh
Gas: 620 TWh
Hydro and other renewables: 410 TWh
PHEVs: 36% of new vehicle sales

For coal to remain a significant source of electricity in a carbon-constrained world, a system for carbon capture and storage is a prerequisite. As a technology, however, carbon capture and storage is still on the horizon. "The largest postcombustion carbon capture system that's been tested is on the order of 2 MW," said Amos Avidan, principal vice president with Bechtel. "The system must be scaled up by a factor of 300 or more to serve the needs of a commercial power plant."

Significant scale-up of underground CO_2 storage is also needed. The largest active storage projects are injecting only up to about 1 million tons per year, and none of them are integrated with a carbon capture technology at a coal-fired power plant. A single 1000-MW coal plant will produce 6 million tons of CO_2 per year, meaning that hundreds of integrated capture and storage systems must be replicated around the world to make a significant impact.

"Scale-up concerns extend beyond the need to develop the infrastructure for injection, which will be on the same order of magnitude as that for extracting oil and gas today," according to Jane Long, associate director at the Lawrence Livermore National Laboratory. "We are fairly confident that sufficient storage capacity exists and that we can characterize underground storage sites, monitor the fate of the injected CO_2, evaluate the risks, and ensure it stays underground. The tougher issues are likely to be how the location of this storage capacity relates to the sources of CO_2, whether we can achieve integration of the effluent rate and the injection rate, ownership of the pore space as the CO_2 spreads out underground, and the assumption of liability over the lifetime of the project."

Boots and Bulldozers

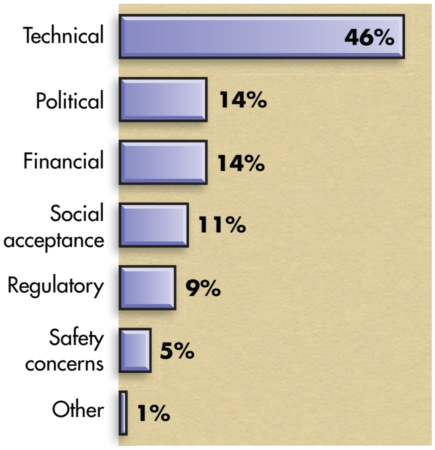
The Summer Seminar also addressed potential strains on manufacturing capacity and the labor pool. Discussion focused on the idea that such strains may be significant for nuclear and coal-fired plant construction, where decades of minimal commercial activity in developed economies have resulted in atrophy of the manufacturing sector and migration of the skilled workforce to other industries.

NEI's Bowman pointed out that the ultraheavy forgings required for major nuclear power plant components such as reactor vessels currently can be manufactured only at one facility, in Japan. The superheavy forgings required for slightly smaller components can be manufactured only at two plants, one in Japan and one in France. Combined, these facilities can support only about five or six new nuclear power plants per year worldwide, assuming other industrial sectors aren't demanding such forgings as well. Resurrecting idled manufacturing capacity, or investing in new capacity, will be required to support an expanded nuclear buildout.

The session "CO_2 Capture and Storage: Making it Work on a Large Scale" examined many technical and nontechnical deployment issues, including how a carbon capture and storage (CCS) industry could spur entirely new business lines. One element certain to challenge rapid deployment is securing the human and physical capital necessary to sustain a CCS industry at scale.

John Tombari, who is a vice president with Schlumberger Carbon Services, outlined how a commercial CCS industry may evolve in the context of a single project. A CCS project would likely proceed through the following steps on its way to commercialization: preliminary study,

Question: What type of challenge to CO_2 reduction will be most difficult?



data acquisition, detailed characterization, design, construction, and injection and monitoring. Each step represents an incremental demand on human resources and capital equipment, and the entire development sequence can take many years.

> "Utility energy efficiency programs in California have saved consumers $5.5 billion over the last decade. That kind of savings can go a long way toward addressing cost concerns some might have about any package of global warming solutions."
>
> Sheryl Carter, Natural Resources Defense Council

For example, three-dimensional seismic analyses are necessary to review the land area bounding a potential sequestration site. The equipment and personnel to conduct such analyses are highly utilized today by the oil and gas industry. "Today, the appropriate 3-D seismic imaging costs about $100,000 per square mile in the United States," said Tombari. "For a typical 500-MW plant, we may need to survey up to 100 square miles, and the seismic work can take six to nine months."

In conjunction with this effort, wells will need to be drilled to gather finer, more-detailed data and samples. A project team comprising geologists, geophysicists, petrophysicists, and reservoir engineers will then be needed to integrate all the data and to build models that will provide both a visualization of the subsurface and a prediction of how the CO_2 might move underground after it has been injected. The team will stay with the project throughout its lifetime, using postinjection monitoring data to refine and rebuild the models.

In short, the resources associated with even a single CCS project are extensive. Multiplying such resource requirements by the thousands of sites worldwide that may deploy CCS technology for CO_2 emissions reduction provides a stark reflection of the dual challenge and opportunity associated with climate change.

David Victor, director of Stanford University's Program on Energy and Sustainable Development, directed the participants' attention to long-term issues of liability. "When you think about injecting CO_2 at scale, it's not that problematic to imagine operation of real sites," said Victor. "But the long-term stewardship questions are really open. None of the companies that would insure these projects would be willing in today's regulatory environment to assume the permanent liability at storage sites long after they have closed operations."

From the audience, Kevin Fitzgerald, managing partner of the Washington, D.C., office of Troutman Sanders LLP, added to this thread by postulating how divergent state property rights across the country could impact the regulation and operation of commercial CCS sites. "If carbon dioxide is going to be a regulated pollutant under the Clean Air Act, it's probably going to be much easier to seek and obtain from Congress some sort of legislation that preempts the diverse and sometimes conflicting state laws concerning liability and property rights and to handle the issue of carbon sequestration in a uniform manner across the United States. Without a uniform approach, the issue of property-owner rights and liabilities could become extremely complicated. We may want to look to the environmental and other statutes that have, in recent decades, successfully preempted various aspects of state law as a way forward to solving that problem."

The Killer App

While the supply side of the electricity meter provides point-source opportunities to reduce CO_2 emissions, Summer Seminar presentations and discussions also focused on the demand side of the Full Portfolio. "We haven't even come close to tapping the potential for cost-effective energy efficiency," said Sheryl Carter, co-director of the energy program for the Natural Resources Defense Council, in the session "Stakeholder Perspectives and Actions." According to Carter, "Utility energy efficiency programs in California have saved consumers $5.5 billion over the last decade. That kind of savings can go a long way toward addressing cost concerns some might have about any package of global warming solutions."

Capturing the voice—and evolving consumption patterns—of the customer can translate into technologies that raise efficiency and lower emissions. "It will be increasingly important for utilities to adjust the business model to better accommodate technologies the regulators and elected officials are pushing, based on what they perceive to be customer interests," said Geesman with the California Energy Commission.

Seminar discussions also were framed by the globalization of customer interests.

“The fate of the world environmentally is in the hands of India and China,” said Jesse Ausubel, director of Rockefeller University’s Program for the Human Environment. “The markets for technologies will be created by consumption in India and China. Whatever India and China buy over the next decades will become what vendors will sell to everybody else, because the economies of scale and manufacturing will be so favorable.”

> “Internet protocol networking is the killer app when it comes to operating a smart grid. IP networking has faced the test of scale, interconnecting millions and millions of end points around the world.”
>
> Scott Lang, SilverSpring Networks

Utility action on energy efficiency can play a big role, particularly if regulators drive incentives. Edison International chairman and CEO John Bryson described California’s success over more than 25 years in encouraging energy efficiency, highlighting the importance of mechanisms that decouple utility revenues from electricity sales. “There is a lot to learn from California, and not all of the many efficiency initiatives were as effective as we originally thought they would be. Others were even better than the initial blueprint. For all of them—and we have more than 40 major efficiency programs, each targeted to specific customer market segments—we have gotten better at achieving cost-effectiveness and customer support through the learning that comes with experience.”

To fully deploy technologies that can enhance economy-wide energy efficiency measures and shape demand response, a robust, flexible, and scalable communications infrastructure is required—one that incorporates universally applied interoperability standards for seamless plug-and-play capability. As Scott Lang, CEO of SilverSpring Networks, explained, “For years the world considered the light bulb to be the killer application for electricity that drove the modernization of our economy. Over time it became clear that the killer app was actually the wall socket and the plug enabling millions of devices to access power from the grid—a truth even more obvious in today’s digital society. Similarly, Internet protocol networking is the killer app when it comes to operating a ‘smart’ grid. IP networking has faced the test of scale, interconnecting millions and millions of end points around the world.” A truly networked environment based on a standard Internet protocol will provide the links between the grid and the customer to enable smart operation and deliver benefits in both emissions and energy savings.

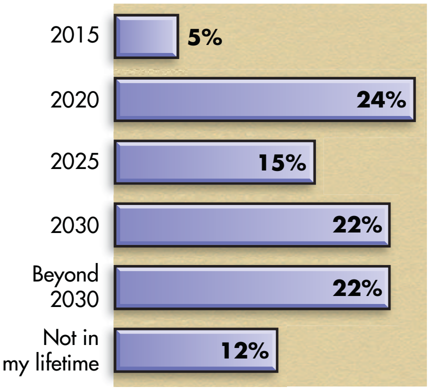
Pay the Piper

The session titled “Creating the Regulatory and Financial Framework to Achieve CO_2 Reduction Goals” drove home the sobering reality that emissions reduction strategies cannot be devised in a vacuum. Policy choices dictate technology choices, and both have economic impacts in terms of consumer electricity prices and capital requirements. Simply put, there will be no free lunch with CO_2 reductions. EPRI’s MERGE economic analysis indicates that, even in a scenario where technology is deployed without constraints to achieve a defined emissions target at minimum cost, consumers should expect price increases. The mitigating agent is technology. “With the Full Portfolio of technologies, our studies indicate that the real price of electricity is going to go up about 45% over the next 40 years,” said EPRI’s Specker. “If we don’t have the Full Portfolio, the increase will be more than 200%.”

Because real electricity prices have consistently declined over the past 50 years, such price increases will be difficult to accept. “At the end of the day, if we want to address global warming, we have to understand the reality that prices are going to go up,” said Michael Morris, chairman, president, and CEO of American Electric Power. “The natural impression of the marketplace, however, is that any increase is a bad increase.”

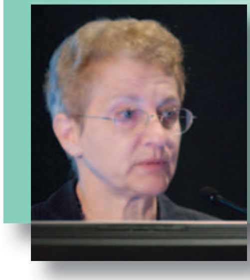
Michael Dworkin, director of the Institute for Energy and Environment at the Vermont Law School, commented from the audience that broader industry experience suggests recognizing the concept of *value* in changing this perception. “We’ve seen in the telecom world that average spending used to be $20 to $25 a month for telephone. Now, when long-distance and local calls are rolled in with cell phone and cable TV and Internet, it’s at a level where many people spend $3500–$4000 a year and

Question: When will CO_2 capture and storage become commercially available?



think that they're getting something worthwhile. So increases, *if* they are combined with a value that, for example, replaces automobile fuel with a plug-in hybrid, or provides better lighting in the home, may mean that electricity costs not only are offset by savings in other parts of family life but can be linked to a significant sense of customer satisfaction."

> "In the absence of a carbon pricing regime, some state regulatory commissions will begin making early investments based upon a feeling that it's the right thing to do for fuel diversity and technological diversity."
>
> Ellen Lapson, Fitch Ratings



The expense of large-scale CO_2 emissions reductions will have to be captured in electricity prices; this reality reflects the substantial capital required to develop and build new nuclear and coal plants and to integrate energy efficiency devices and renewable energy. Bechtel's Avidan highlighted the sharp escalation in construction costs for large coal plants. Over the past three years, the cost of engineering, procurement, and construction for coal plants—which does not include the additional capital required for owners' costs, carrying charges, and contingencies—has risen by 66%, from $1200/kW to $2000/kW. "Although there are signs of moderation in some of the commodity markets," said Avidan, "with the global pressure on the infrastructure industry, it's hard to forecast where prices are heading."

Seminar participants considered the murky crystal ball of finance. Applying a conservative $1500/kW capital cost to the estimated 350 GW of new generating capacity that will be required in the United States to satisfy incremental demand through 2030 results in an overall price tag of $525 billion. As technology implementation costs go up, the companies providing this capital must have some reasonable assurance of return on investment. "Unless there's clarity on how these big dollars are going to be recovered and earn adequate return, the big dollars are never going to flow into the sector," said Kevin Genieser, managing director with Morgan Stanley.

The Full Portfolio will be realized only if amenable regulatory and market structures are in place, through some mix of loan guarantees, subsidies, tax credits, and, ultimately, a real or implied price on carbon. "I am optimistic about the dynamism of our financial markets to provide capital," said Ellen Lapson, managing director with Fitch Ratings. "Reasonable investment outcomes can be predicted if we have relatively stable regulatory structures. In the absence of a carbon pricing regime, some state regulatory commissions will begin making early investments based upon a feeling that it's the right thing to do for fuel diversity and technological diversity."

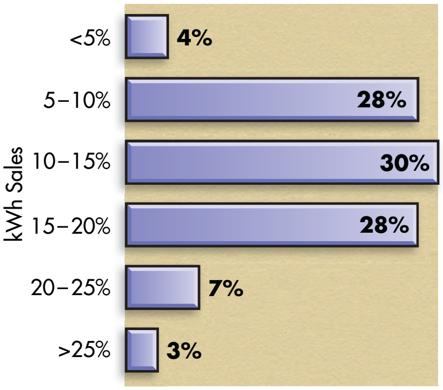
Technology On or Off the Shelf? The Critical Role of R&D

The great unknown when evaluating the economics of climate change policy is the price of carbon. "Whether it's through a cap-and-trade system, a carbon tax, or some other mechanism, no private actor is going to do anything unless the effective price of carbon dioxide is $35 per ton or greater," according to Carnegie Mellon's Morgan.

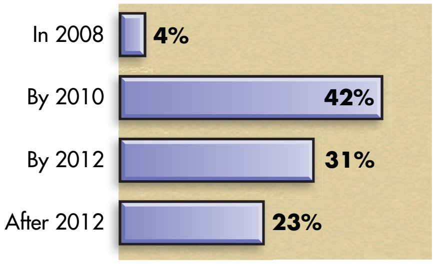
When companies do act, they want a broad suite of options available to minimize compliance costs. "Market-based measures like cap-and-trade are very good at bringing the technologies off the shelf that aren't cost effective without that carbon price," said Anne Smith, vice president with CRA International. "But carbon prices are really not at all effective at getting those new technologies onto the shelf so that they're ready to be used on a commercial basis."

One reason for this is the long lead time for technology R&D. If technology is to be available to deal with emissions economically, the R&D choices and commitments must be made years—sometimes decades—before the pricing signals appear. In addition, market-based pricing strategies such as cap-and-trade systems create prices "in the moment," making them difficult to predict years ahead. "We're not likely to adopt a price trajectory that is strong enough to accelerate technologies," said Phil Sharp,

Question: What reduction can energy efficiency provide in electricity use by 2020?



Question: When will mandatory CO_2 controls be placed on the electricity sector?



president of Resources for the Future. Beyond pricing signals, therefore, other policies will be needed to develop, demonstrate, and deploy the technologies that will address climate change concerns. "R&D takes a little bit more.... There needs to be certainty for investors that they will be able to obtain and retain intellectual property rights," said CRA's Smith. "Impermanence and uncertainty are anathema to getting the right policy setting to meet the technology challenge."

The seminar participants discussed volatile fuel prices, rising capital investment costs, and environmental issues that will significantly complicate regulatory decisions moving forward. Technologies won't necessarily make these decisions easier, but technology provides options that increase the likelihood that decisions will have fewer negative impacts. "We have to redefine what the term *failure* means," said PNM Resources' Sterba. "When we think about new technology, we have to be willing to take some risk, and sometimes this means we're going to pay more for something that has a lower probability of success than the tried-and-true technology. If that is viewed as a failure by the regulator, it won't happen again."

> "Everybody wants to be the fifth deployer of a new technology at commercial scale. Someone's got to be brave enough to stand up once, twice—three or four times."
>
> Carl Bauer, U.S. Department of Energy
> National Energy Technology Laboratory

There are limits, however, to what regulators and public commissions can do to address and enable emissions reductions. "PRISM is exactly the kind of approach state regulators across the country are looking for," said James Kerr II, president of the National Association of Regulatory Utility Commissioners and a commissioner with the North Carolina Utilities Commission. "The one shortcoming is that we don't have the luxury of waiting for these technological solutions. When we get home tomorrow, we have to meet the demand that is before us. That said, in a time when we are all searching for answers, this analysis provides at least two—technology and R&D."

Failure Is Not an Option

In the end, while regulators, policymakers, interest groups, and the public are integral to making the climate change solution more palatable, the electricity sector must be willing to stick its neck out. "If we have said—and I think correctly and effectively—that climate change really is a technology challenge, we've got to walk the talk," said Sterba. "We've got to be willing to invest in technology."

"Having a technology ready to go that has commercial viability doesn't mean it's deployed," said Carl Bauer, director of the U.S. Department of Energy's National Energy Technology Laboratory. "It means it has passed a reasonable scale of demonstration, the economics and performance are reasonably understood; and yet nobody's ready to commit to large-scale deployment. Everybody wants to be the fifth deployer of a new technology at commercial scale. Someone's got to be brave enough to stand up once, twice—three or four times."

Audience member Stephen Lennon, managing director of resources and strategy with ESKOM, picked up on this issue. "We need to start factoring things such as the cost of CO_2 into our investment decisions. Some of that is being done, but we should take it more seriously. Power companies are also big buyers. If we entrench things such as energy efficiency and low-emitting processes as requirements for our suppliers throughout our procurement practices, this can make a big difference."

Narrowing the gap between technology development and commercial availability is paramount. As part of the Full Portfolio analyses, EPRI has defined four technology pathways where concerted action in research, development, large-sale demonstration, and diverse deployment could accelerate CO_2 emissions reductions in the electricity sector. These pathways are described in detail later in this issue (see "Pathways to the Full Portfolio," p. 20).

The operative word is *action*—moving "from theology to rational action," in the words of Jeff Sterba. The only certainty with global climate change is that the path will be tortuous. Technology, however, can play a critical dual role: navigating the path to ensure the destination is reached, and smoothing the bumps to ensure the passengers don't suffer unnecessary harm.

"I don't think we can assume we're going to throw away the last 100 years of electricity price declines and move into a world for our kids and grandkids where real prices go up 200%," said Specker. "As a technologist, I think that's failure. The projected trajectories for electricity prices and electricity sector CO_2 emissions are both unacceptable. We *can* decarbonize the electricity sector and do it in a way that electricity prices don't go through the roof."

This article was written by Brian Schimmoller (bschimmoller@epri.com).

Modeling the

Technology Mix

The Story in Brief

The electricity industry is now actively considering which combination of advanced technologies can best meet CO_2 emissions reduction targets. The fundamental challenge is to develop a portfolio of options that is technically feasible and can provide affordable electricity to customers. As the industry considers its investments in research, development, and demonstration projects, EPRI's PRISM and MERGE analyses address this challenge and point toward a solution that EPRI describes as "The Full Portfolio."

The EPRI Summer Seminar held in August 2007 produced a surprisingly strong consensus among its diverse participants: Development of a portfolio of advanced technologies is the most challenging but by far the most promising approach for the electricity sector to reduce its CO_2 emissions. In anticipation of future CO_2 emissions policies, EPRI has analyzed the technical potential for the U.S. electricity sector to reduce emissions over the next 25 years and has assessed the economic benefits of using advanced technologies to achieve required reductions. The result: If the U.S. electricity sector deploys a full portfolio of technologies rather than a more limited one, the overall cost of emissions reductions to the U.S. economy could be lowered by as much as one trillion dollars.

The anticipation of national regulation is already driving extensive efforts to develop technologies that can reduce emissions of CO_2 and other greenhouse gases. Major government and private industry research programs are focused on advanced nuclear power plants, carbon capture and storage for coal plants, a variety of renewable energy resources, and diverse technologies to increase end-use energy efficiency. What has largely been lacking, however, is a clear vision of how to create a portfolio of technologies optimally suited for reducing CO_2 emissions from the electricity sector, as well as an assessment of the economic advantages of widely deploying these technologies.

To clarify the range of features for such a portfolio, EPRI has considered two cases—one with a limited range of R&D investment and resulting technology deployments and another with a more comprehensive set of R&D targets and technology deployments. The latter has become known as the Full Portfolio. A comparison of the two approaches highlights differences of both degree and kind. The limited portfolio focuses primarily on evolutionary improvements in conventional coal- and gas-fired generation, further development of renewable technologies, and increases in end-use efficiency. While ongoing technical improvements would ensure that today's fleet of nuclear plants continue to operate effectively, nuclear capacity would remain at existing levels.

The Full Portfolio includes all of the developments of the limited portfolio but adds technology that will increase capabilities beyond evolutionary improvements. For example, the development of a "smart" electricity grid and commercialization of plug-in hybrid electric vehicles would greatly accelerate improvements in end-use efficiency; and the deployment of energy storage technologies would increase the cost-effectiveness of intermittent renewable generation. Even more important for the Full Portfolio are two large-scale developments that would not be available under a limited approach: U.S. deployment of advanced light water reactors, which would substantially increase the number of nuclear plants, and carbon capture and storage technology, which would drastically reduce CO_2 emissions from coal-fired plants.

Consideration of these portfolio options leads to two fundamental questions: Can the technologies being considered indeed reduce greenhouse gas emissions to desired levels, and what is their economic value? To help answer those questions, EPRI recently completed two related studies. The first, the so-called PRISM analysis, assessed the U.S. electricity sector's technical *potential* for reducing CO_2 emissions, assuming deployment of the Full Portfolio of advanced technologies. A separate analysis, MERGE, calculated the economic value of deploying these technologies and projected the least-cost combination of technologies needed to meet assumed CO_2 emissions reduction targets representative of potential policies. These results inform EPRI's ongoing efforts to identify the research, development, and demonstration (RD&D) pathways to successful and economical CO_2 emissions reductions (see "Pathways to the Full Portfolio," page 20).

Calculating Technical Potential

The PRISM analysis assumed that the industry could achieve "aggressive but feasible" targets for deploying seven advanced technology options:

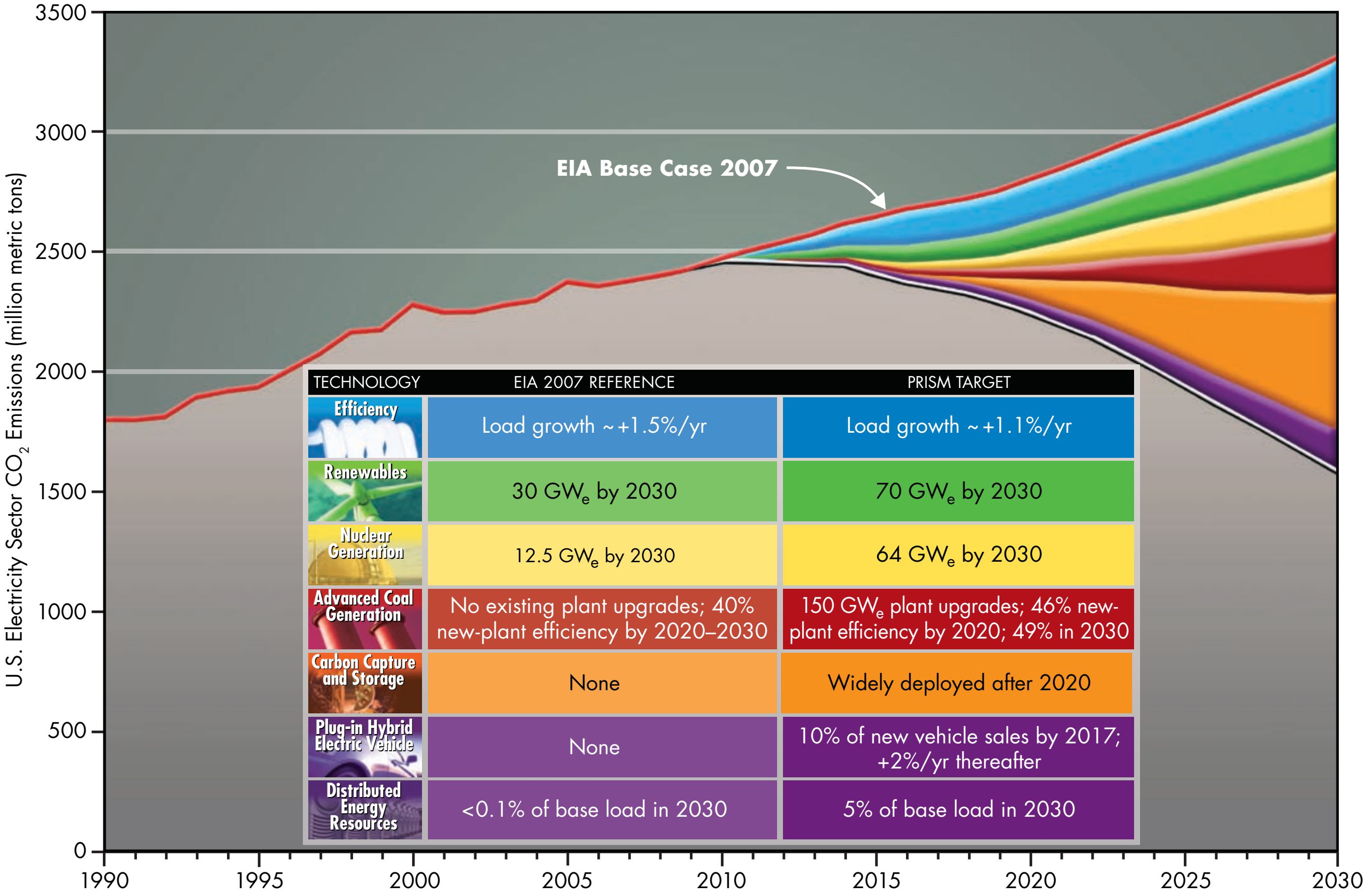
- end-use energy efficiency
- renewable energy
- advanced light water nuclear reactors (ALWRs) and life extension for existing reactors
- advanced coal power plants
- CO_2 capture and storage (CCS)
- plug-in hybrid electric vehicles (PHEVs)
- distributed energy resources (DER)

The calculated potential for CO_2 emissions reductions was based solely on the technical capabilities, assuming no economic or policy constraints.

The PRISM analysis gets its name from EPRI's graphic representation of the Full Portfolio's broad spectrum of emissions reduction technologies. In comparison with the base case projections of the Energy Information Administration (EIA) in its 2007 *Annual Energy Outlook,* the PRISM results show that aggressive deployment of the Full Portfolio of advanced technologies could reduce CO_2 emissions levels by about 45% in 2030. "The analysis also showed there is no 'silver bullet' for reducing emissions," says Revis James, director of the EPRI Energy Technology Assessment Center, which conducted the PRISM analysis. "Rather, the results show that a diverse combination of new and existing technologies will be required. By deploying a full portfolio of such technologies, the electricity sector can make a very substantial contribution to reducing U.S. CO_2 emissions."

Aggressive Assumptions: How Best to Anticipate the Future?

For each technology considered, the PRISM analysis uses aggressive assumptions regarding technology performance and deployment and then calculates changes in electricity consumption and the generation mix resulting from a technology portfolio based on these assumptions. Finally, it determines CO_2 emissions reductions resulting from this transformation. A key underlying assumption is that



TECHNOLOGY	EIA 2007 REFERENCE	PRISM TARGET
Efficiency	Load growth ~+1.5%/yr	Load growth ~+1.1%/yr
Renewables	30 GW_e by 2030	70 GW_e by 2030
Nuclear Generation	12.5 GW_e by 2030	64 GW_e by 2030
Advanced Coal Generation	No existing plant upgrades; 40% new-plant efficiency by 2020–2030	150 GW_e plant upgrades; 46% new-plant efficiency by 2020; 49% in 2030
Carbon Capture and Storage	None	Widely deployed after 2020
Plug-in Hybrid Electric Vehicle	None	10% of new vehicle sales by 2017; +2%/yr thereafter
Distributed Energy Resources	<0.1% of base load in 2030	5% of base load in 2030

Potential CO_2 Reductions: *EPRI's PRISM analysis assessed the U.S. electricity sector's technical potential for reducing CO_2 emissions to 1990 levels by 2030—a goal considered critical for stabilizing atmospheric concentrations. Starting with the Energy Information Administration's* Annual Energy Outlook *2007 estimates as the base case, researchers calculated what additional reductions could result from accelerated development of a wide range of advanced technologies. While the EPRI targets are very aggressive, achieving the desired reductions is technically feasible.*

a specific sequence of RD&D activities could be identified that would achieve wide-scale deployment of the advanced technologies by 2030. In most cases, EPRI's deployment assumptions are considerably more ambitious than those used in the EIA base case analysis.

The PRISM assumption for nuclear power deployment, for example, is 64 GW of new capacity by 2030, compared with 12.5 GW in the EIA analysis. This larger assumption is supported by two particularly promising points: much of the new capacity could be added at existing nuclear sites, and the ALWR technology that would provide the basis for these new plants is well developed and is already being used in several countries.

Another major departure from the EIA base case involves CCS technology, which the EIA analysis did not include. The PRISM assumption—based on milestones established in a technology development roadmap jointly created by EPRI and the Coal Utilization Research Council—holds that CCS technology can be widely available and deployed after 2020, presuming that the large-scale CCS demonstration program sponsored by the U.S. Department of Energy is successful and is completed on schedule. The PRISM analysis also adopts in its estimates the development roadmap's targets for improving thermodynamic performance and heat rates at pulverized-coal plants and integrated gasification–combined-cycle coal plants.

With regard to end-use efficiency, the PRISM analysis assumes that the Energy Policy Act of 2005 mandate of a 20% energy intensity improvement for federal buildings will be extended to all consumption sectors. This would result in average annual electricity demand growth of only 1.1% between 2005 and 2030—about 30% less than the comparable EIA base case figure. An important technological component of meeting this target will be the development of a "smart" distribution system, incorporating distributed sensors and advanced metering, to enable greater automated control of electricity consumption.

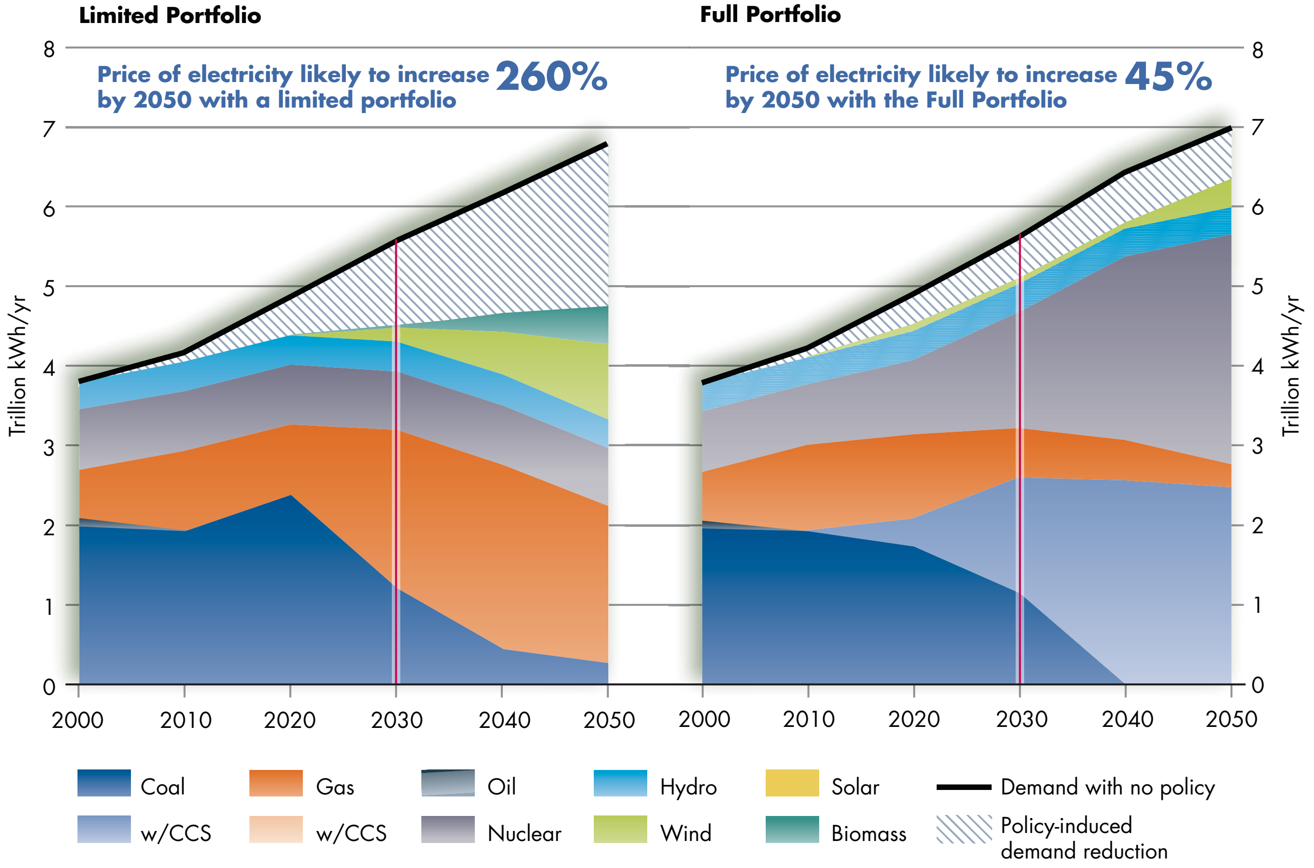
The PRISM analysis assumes that nonhydro renewable energy capacity will continue to grow at a rate of 2 GW/year from 2020 to 2030, resulting in a total capacity of 70 GW by 2030—more than twice the EIA base case projection. This increased capacity is assumed to include widespread deployment of intermittent resources, such as wind and solar, facilitated by ongoing changes in utility transmission and distribution systems. EPRI's renewables deployment assumption matches the combined requirements of existing state-mandated renewable portfolio standards.

The study also established assumptions for two technologies not owned or controlled by utilities—PHEVs and DER. In the case of PHEVs, an aggressive assumption is made: 16% market penetration for new light-duty vehicles by 2020 and 30% by 2030, compared with no consideration of this technology in the EIA base case. Similarly, PRISM assumes that DER will represent 5% of baseload generation by 2030, compared with the EIA assumption of less than 0.1%.

"PRISM's aggressive targets really push the envelope, and its projected generation mix for 2030 is very different from that envisioned by the EIA base case," observes Bryan Hannigan, vice president of EPRI's Environment sector and a major force in the model's creation. "In particular, the PRISM results show much greater use of nuclear power, renewable energy, and coal with CCS, and a sharply lower contribution from natural gas and coal without CCS."

The MERGE Analysis and the Full Portfolio

What are the potential economic impacts of deploying the Full Portfolio versus a limited technology portfolio? In a general equilibrium economic model called MERGE (model for estimating the regional and global effects of greenhouse gas reductions), EPRI researchers modeled outcomes based on projected capital and operating costs of these technologies, together with assumed generic CO_2 emissions constraints in line with potential policies. MERGE has been used by climate scientists for more than a decade to analyze the lowest-cost technology mix that is able to achieve a specified CO_2 emissions constraint as a function of tech-



Price of electricity likely to increase **260%** by 2050 with a limited portfolio

Price of electricity likely to increase **45%** by 2050 with the Full Portfolio

Generation Mix: *Under a limited portfolio scenario, natural gas becomes the dominant generation fuel by 2030, and* CO_2 *reduction policies can only be met through large reductions in electricity demand, placing severe constraints on economic growth. With the Full Portfolio, nuclear power and advanced coal generation with carbon capture and storage reduce emissions to the point where a much lower demand reduction is needed. By 2050, the Full Portfolio will have essentially de-carbonized the electricity sector and reduced the impact on electricity prices to less than a fifth that of the limited portfolio.*

nology cost, availability, and performance.

MERGE can project energy production for each technology, wholesale electricity prices, CO_2 emissions allowance prices, and the costs to the overall U.S. economy of the specified emissions reduction constraint. All MERGE monetary outputs are in constant 2000 dollars.

The analysis showed that the economic impacts of pursuing the Full Portfolio versus the limited portfolio are significant. Several CO_2 reduction profiles—reflecting the requirements of different future emissions policies—were examined using MERGE; for each combination of technology scenario and policy constraint, the MERGE model calculated the economic cost to the U.S. gross domestic product over the analysis period. The policy assumption considered here is the one that most closely resembles the PRISM emissions profile—an intermediate case widely discussed by policymakers that stabilizes emissions from 2010 to 2020 and then reduces them by 3% per year. For this case, the economic cost to GDP associated with the limited portfolio scenario was calculated to be $1.5 trillion. This could be reduced to roughly $0.5 trillion through availability of the advanced technologies in the Full Portfolio scenario. The MERGE analysis showed that reliance on any single technology would not come near to achieving the reduction in policy cost that could be achieved by using them all together.

Even when an economically efficient path for CO_2 emissions reduction is pursued, the wholesale price of electricity is likely to rise substantially as emissions are restricted. However, the MERGE analysis makes it clear that the increase will be much lower and will stabilize if advanced technologies are deployed. Assuming an intermediate emissions policy, the real price of electricity is projected to increase about 45% by 2050 with the Full Portfolio, compared with a 260% increase in the limited portfolio scenario. In addition, implementation of the Full Portfolio would lead to nearly full de-carbonization of the electricity sector by 2050.

The MERGE analysis shows how this change will occur by tracing the impact of technology availability on the U.S. generation mix. Under the emissions constraint discussed here, the model points to a drastically different deployment of generation technologies under the limited portfolio scenario after about 2020. Assuming that CCS would not be available to help meet the emissions constraint, the use of coal would fall off sharply and coal would be largely replaced by natural gas. Moreover, there would be a profound reduction in the demand for electricity, driven by very high prices. With the Full Portfolio, however, the availability of CCS would allow coal to be maintained, taking on a new role as a non-emitting generation option. At the same time, aggressive technology deployment would enable nuclear power to expand greatly, while natural gas would essentially maintain its current position as a fuel of choice for peaking units.

Wider Implications

By illustrating the critical interactions among various sectors of the economy, EPRI's MERGE analysis identifies wider implications of carbon constraints on electricity technology evolution. For example, if the electricity sector must replace coal with natural gas in the limited portfolio scenario, sharp increases in natural gas prices could result. In terms of constant 2000 dollars, the wellhead price of natural gas could rise from the current level of about $6/thousand cubic feet (MCF) to around $13/MCF by 2050. With the Full Portfolio, the price is likely to rise to only about $10/MCF. The contrast between the two scenarios is even greater in terms of natural gas consumption, which would be more than two-and-a-half times greater in 2050 for the limited portfolio. With the Full Portfolio deployed, the economy could reduce both its overall consumption of natural gas and the share used for electricity generation between now and 2050.

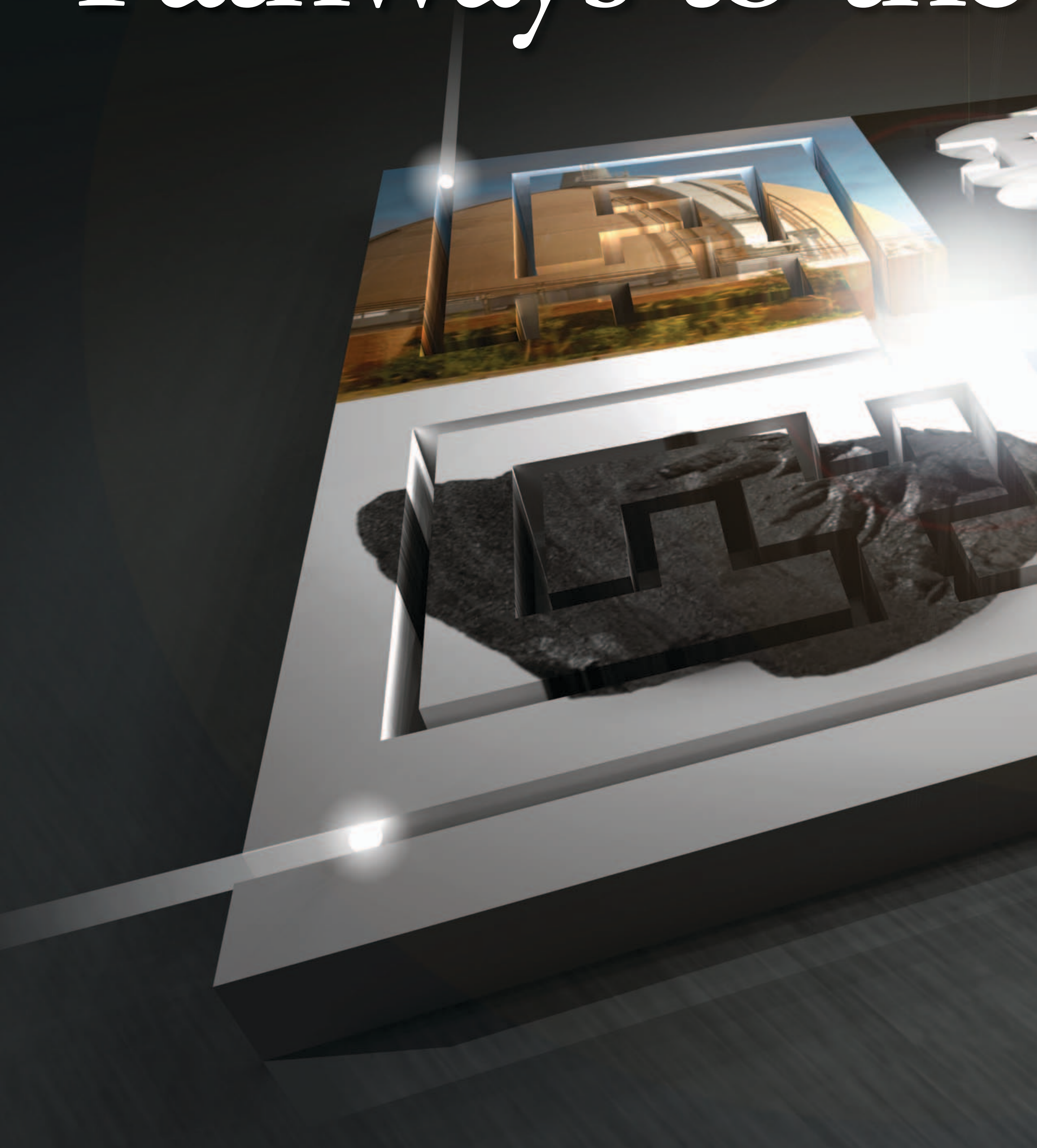
MERGE projects a similarly dramatic contrast in the projected price of CO_2 emissions. With limited technology development, the economy-wide cost of enforcing emissions constraints would grow very rapidly, driving up the real price (in year 2000 dollars) of CO_2 to more than $300/ton by 2050 in the intermediate policy case. The Full Portfolio would enable electricity sector emissions to fall, so the price of CO_2 would rise more slowly, reaching about $150/ton by 2050. At this point the electricity sector would be essentially decarbonized, and any further CO_2 reductions would have to come from industry, transportation, and other non-electric segments of the economy.

Such price differences provide a strong incentive to develop and deploy advanced electricity-related technologies. They also support the conclusion of other analyses that electric power will increasingly be used to provide low-carbon energy throughout the economy. The Full Portfolio scenario leads to accelerated electrification of other sectors of the economy, as consumption of electricity relative to non-electric energy use more than doubles by 2050, with an even greater increase under an emissions constraint.

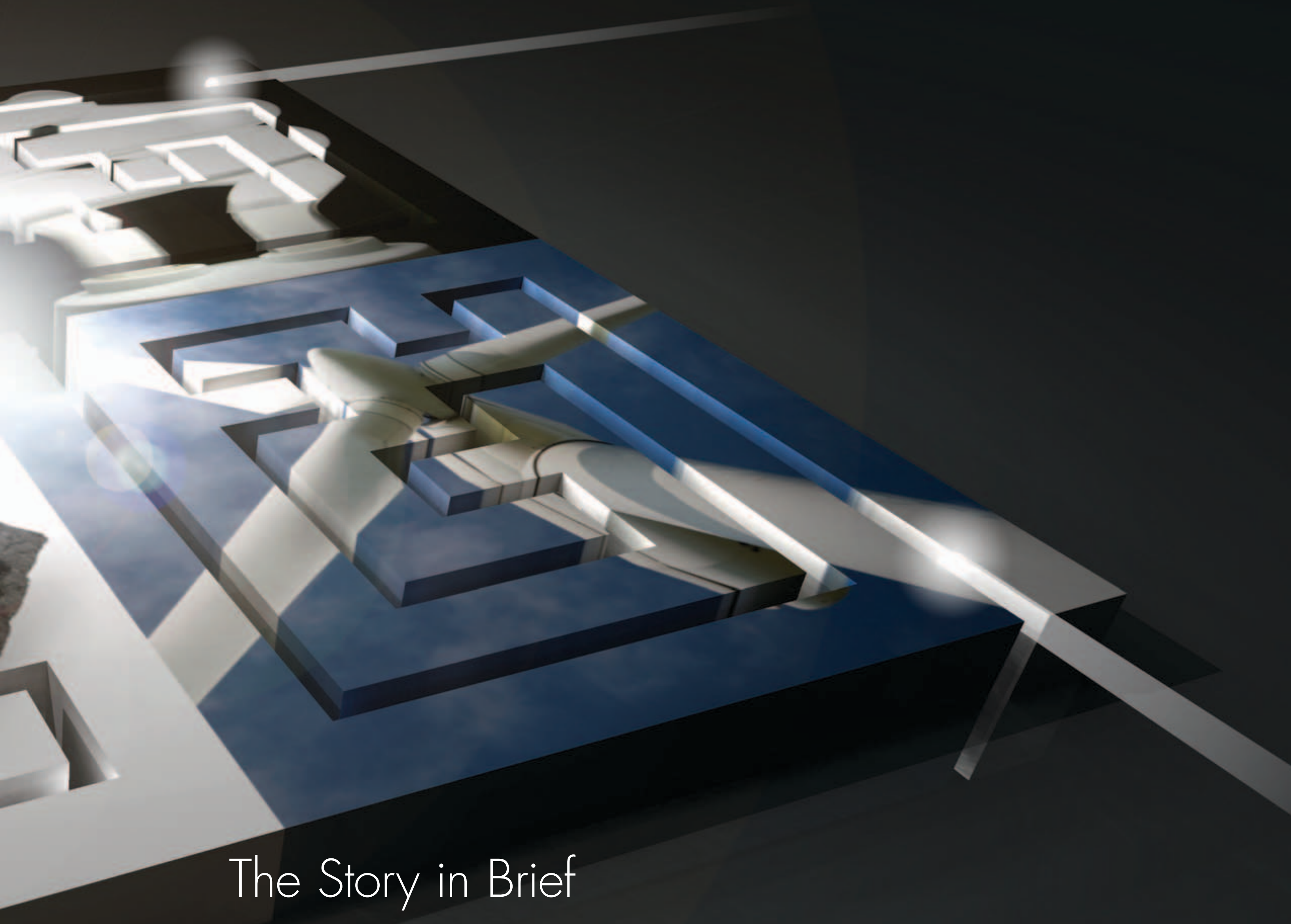
"It's important to remember that these figures are not chiseled in stone," concludes Richard Richels, senior technical executive for EPRI's global climate change research. "What we have tried to analyze in MERGE are the economic advantages that could be realized by using advanced technologies to limit CO_2 emissions. To get realistic estimates, we have restricted ourselves to technological advances that can be foreseen with some level of confidence. However, history has taught us to expect significant—though unpredictable—breakthroughs as well, and policy incentives may also accelerate the process."

This article was written by John Douglas. Background information was provided by Revis James (rejames@epri.com), Geoff Blanford (gblanford@epri.com), and Steve Gehl (sgehl@epri.com).

Pathways to the



Full Portfolio



The Story in Brief

Discussions at EPRI's Summer Seminar made one point clear: If the U.S. electricity sector is to reduce its carbon dioxide emissions substantially, then research, development, and demonstration (RD&D) of major technologies must start *now*. If the Full Portfolio of technology options becomes the industry's ultimate destination, then the question to be answered is, how does the industry arrive there? EPRI has identified four technology pathways to answer that question and serve as the framework for a robust RD&D agenda.

Going into the 2007 Summer Seminar, the participants were broadly familiar with the critical areas of research that must be pursued over the next few decades, but through the day-and-a-half discussion, they came to more fully appreciate the scope, long lead times, and interdependencies of the RD&D process. Work must proceed in a logical manner, one technical milestone building upon another, with the scale-up of major systems proceeding in proven increments until they reach full commercial operation. Each of the technology sectors faces different challenges, some having to overcome high-risk technology hurdles while others face fewer technology challenges but greater deployment challenges. In any case, given the broad technology requirements of the PRISM analysis, it is clear that a comprehensive program of RD&D must start immediately for all sectors if the Full Portfolio of technologies is to be deployed successfully. The electricity sector is faced with questions of how to combine public and private efforts that are focused and sustained, as well as how to move forward without necessarily waiting for the political process to nail down the fine details of greenhouse gas emissions policy.

The entire suite of CO_2 reduction technologies must progress in parallel in order for the Full Portfolio of technologies to be deployed. A manageable plan must provide structure to all of the required RD&D activities without losing sight of strategic objectives. EPRI has started by laying out four strategic technology pathways to accelerate progress in distribution, transmission, nuclear, and coal technologies. The first two pathways constitute the creation of a smart grid that will enable contributions to CO_2 reductions from renewables, energy efficiency, distributed energy resources, and plug-in hybrid electric vehicles. The latter two pathways are designed to ensure the viability of coal and the accelerated expansion of nuclear power—the two workhorses of electricity supply, which account for more than 70% of current U.S. electricity generation.

Each technology pathway involves an ambitious sequence of RD&D steps that achieve critical targets in the 2015–2030 period. The four pathways presented at the 2007 Summer Seminar and discussed in this article will form the basis for EPRI's comprehensive RD&D action plan.

DISTRIBUTION-ENABLED TECHNOLOGIES

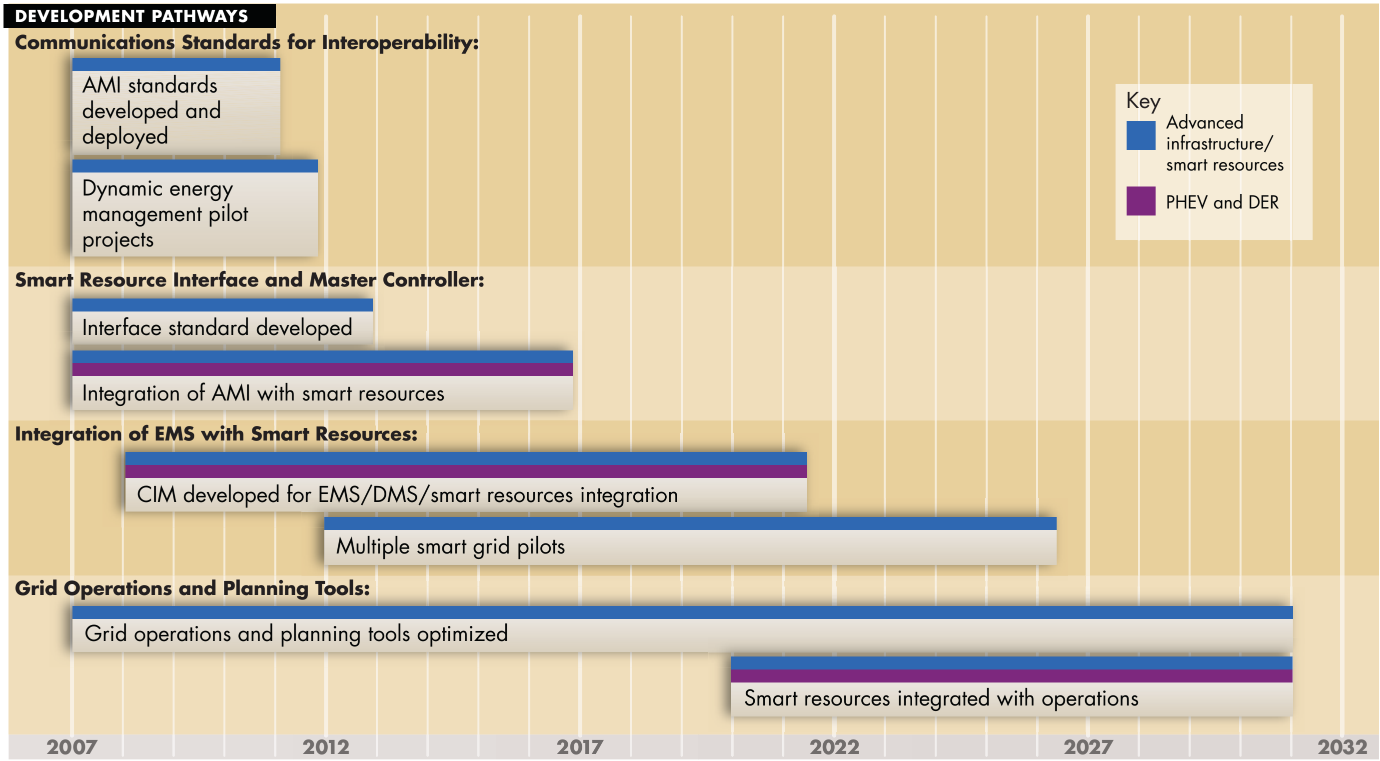
Efficiency, Plug-In Electric Vehicles, Distributed Energy Resources

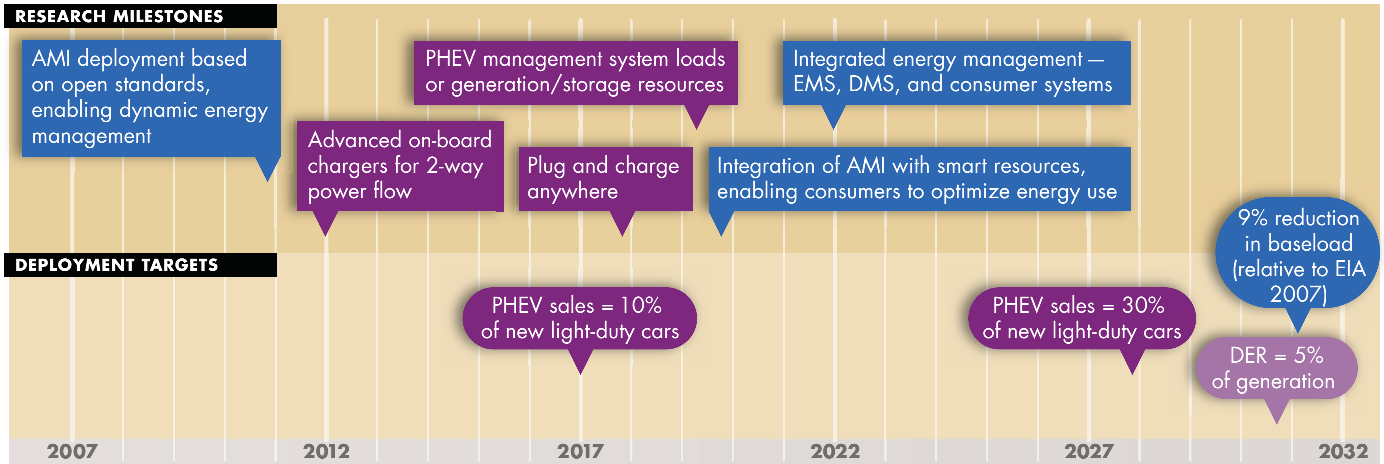
While commercial companies are actively developing the capabilities of energy-efficient end-use devices, distributed energy resources (DER), and plug-in hybrid electric vehicles (PHEVs), the real payoff for these technologies will come when they can be widely deployed and integrated into an "intelligent" distribution network. This interactive distribution system will enable these elements to work together via a standard Internet Protocol (IP), using a "universal language" for communication between devices. The resulting digital platform will enable millions of IP-addressed smart devices, appliances, machines, databases, and control systems to communicate, to synchronize operations, and to respond to price signals.

Arshad Mansoor, vice president of EPRI's Power Delivery and Utilization sector, compares this evolution to the creation of the USB (Universal Serial Bus) port on today's computers, which allows memory sticks, digital cameras, and computer peripherals from different companies to be plugged in directly. "Interoperability standards are the USB of the distribution system," Mansoor says. "With them we will have seamless plug-and-play capabilities with today's electricity network. We will be able to connect generation resources of various types and scales, transmission assets, distribution systems, and a wide array of end-use equipment."

> An IP-based smart grid will allow seamless connection of generation resources of various types and scales, transmission assets, distribution systems, and a wide array of end-use equipment.

Mansoor says that aggressive and successful RD&D efforts can make this critical plug-and-play capability a reality by 2015 and universal by 2020. To meet such a goal, interoperability standards must be in place by 2010, along with an advanced metering infrastructure (AMI) that will support real-time data acquisition and dynamic energy management. Pilot projects that confirm such energy management capability must be completed by 2012,





and the integration of AMI with smart distributed resources must be accomplished by 2015. This step involves assurance that DER and end-use devices are routinely manufactured to include interactive intelligence and accepted communication standards. After 2015, the integration will step up systematically from the distribution level to the energy management systems level—and finally to grid operations and planning, sometime in the 2020s.

Mansoor points out that with an intelligent network, energy efficiency and demand response don't have to be regarded as two different things. "If you change high-intensity commercial lighting from magnetic ballasts to electronic ballasts, you gain efficiency; but more important, you now have a dispatchable resource, because you can dim those lights when you need to. That's really the key concept. You can make it efficient and you can make it smart at the same time. We are just scratching the surface of what will be possible with a smart grid," Mansoor says.

Energy efficiency technologies provide many of the most cost-effective near-term options for CO_2 emissions reduction because many can be deployed faster and at lower cost than supply-side options. Efficiency opportunities are particularly ripe in the electronics area, for three reasons. First, electronic devices represent the fastest-growing portion of residential and commercial load, expected to account for at least 30% of residential electricity consumption by 2030. Second, electronics are naturally suited to carry the embedded intelligence that can be harnessed to foster energy efficiency in the devices and appliances they operate. And third, because electronics manufacturers have so far paid little attention to energy efficiency, substantial gains can be made in this area.

A good example are the millions of small plug-in power supplies that convert 120-volt ac power to low-voltage dc for cell phones, laptop computers, video games, and other digital devices. About 6–8% of U.S. electricity now flows through these converters, with energy losses in the range of 40–50%. Plasma TVs, which are just beginning large-scale penetration of the home market, are also large energy consumers, using three to four times more power than conventional TVs. When TV goes exclusively to digital broadcast in early 2009, converter boxes will be needed for the 120 million analog TVs still in use. "Each box can draw as much as 30 watts, 24 hours a day, 365 days a year," says Mansoor. "That's half a refrigerator." He refers to this growing electronic demand as "load bloat" and proposes that the electricity sector start working closely with electronics manufacturers to elevate the priority of energy efficiency in their designs.

PHEVs may also play a significant role in an intelligent energy network. Their large, easily charged racks of advanced batteries could serve as a distributed energy resource, providing emergency electricity supply to homes and increased grid stability to the network at large. PHEVs have also been shown to offer substantial environmental improvements over the conventional vehicles they will replace. A recent study by EPRI and the Natural Resources Defense Council showed the potential for large-scale CO_2 emissions reductions by PHEVs under a variety of scenarios. Net environmental benefits resulted in all cases, but dramatic benefits were projected in cases of high market penetration by PHEVs.

With technical advances and market acceptance, PHEVs should enter the U.S. market around 2010 and could account for 10% of new-car sales by 2017. EPRI's distribution-enabled pathway calls for the development of an advanced on-board charger for handling two-way power flow by 2012. With aggressive RD&D, PHEVs could be fully integrated into the smart distribution system by 2020; once there, they could be managed as an aggregated storage resource to meet peak loads and emergencies and to provide ancillary services.

TRANSMISSION-ENABLED TECHNOLOGIES

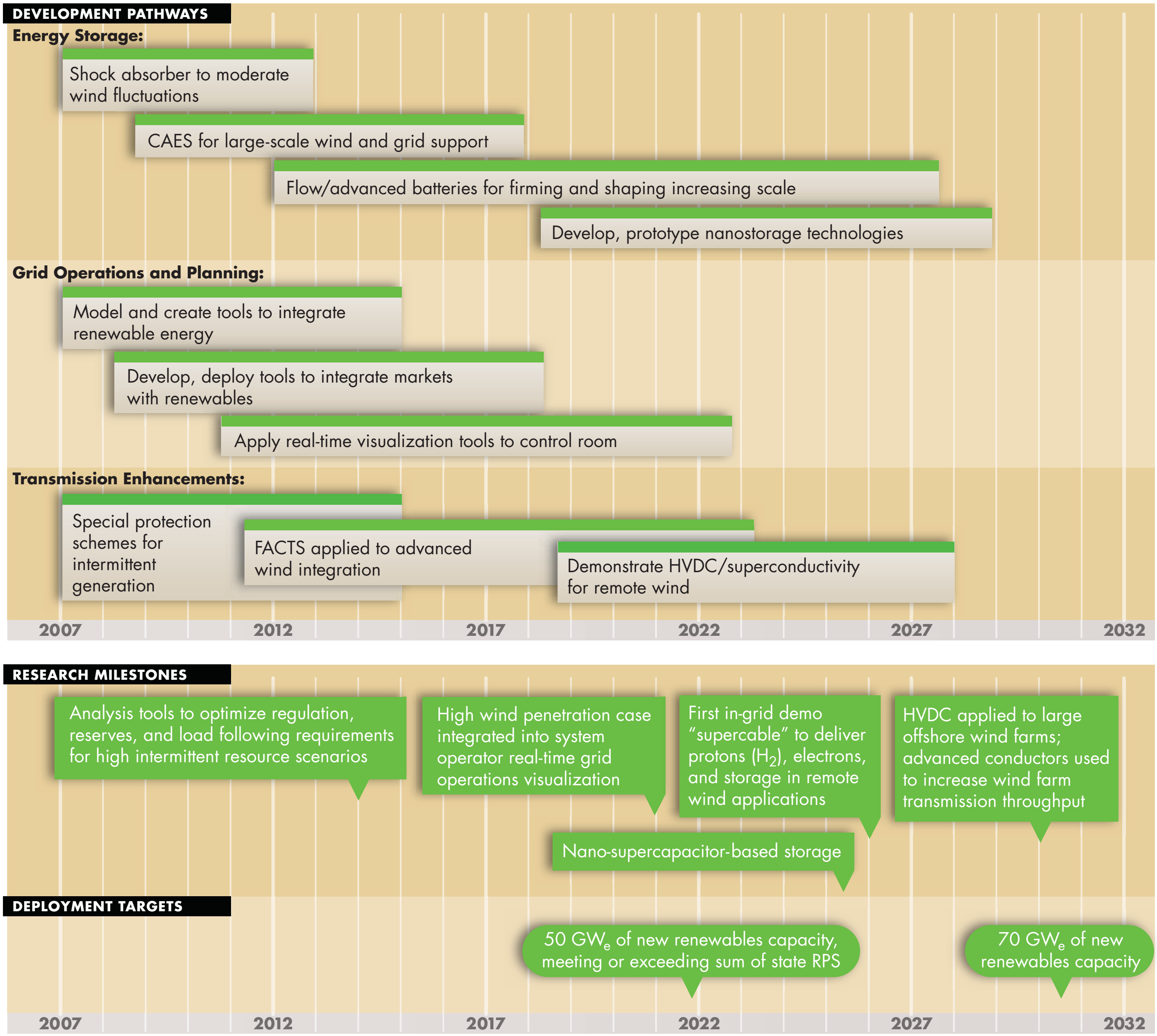
Intermittent Renewables

According to the PRISM assumptions, wind, biomass, geothermal, incremental hydro, and solar power could increase the renewable component of generation more than tenfold over the next 25 years. To accommodate such growth in energy resources that are inherently less controllable than conventional generation, the transmission system must be enhanced to become more resilient and flexible. Bulk energy storage must become an integral part of the electricity supply chain. EPRI's second strategic technology pathway calls for a transmission grid infrastructure that can operate reliably with as much as 20–30% intermittent renewables in specific areas—particularly the wind-rich regions of the United States.

Already in some areas in New Mexico and California, wind accounts for 10–15% of total capacity, and even higher penetrations can be found on some European grids. In the upper Midwest and California, relatively high penetration levels are handled by a strong transmission backbone and by relying on other (controllable) generation options, such as gas turbines and hydro, to even out the flow of power. In other geographic areas, wind farm generation has been curtailed by transmission limitations and less backup flexibility.

> Bulk energy storage and advanced power electronics must become an integral part of the electricity supply chain if intermittent renewables technologies are to reach full potential.

Wind power provides the most striking example of the technical challenges facing large-scale grid integration of intermittent resources. Potential remedies include better wind turbines, improved fault tolerances, more-accurate wind forecasting, power electronics for stabilization and compensation, and energy storage. Of these, only storage offers a comprehensive solution to the grid challenges of intermittent generation. Storage can firm up power supply and provide frequency regulation,



reactive power control, spinning reserve, and grid investment deferral.

"When you have intermittent resources," says Arshad Mansoor, "you need more-advanced control and monitoring technology, but the real key will be large-scale storage. There are a number of technologies out there—compressed air energy storage (CAES), advanced batteries, ultracapacitors, flywheels, and in the longer term (e.g., by 2025), nanostorage technologies." The RD&D pathway calls for accelerated CAES development and demonstration through 2017, continuing work on advanced batteries through 2025, and a prototype of a nano-supercapacitor-based storage device by 2025.

While advanced storage will take time, Mansoor says, CAES offers some immediate opportunities at the 5–15-MW scale. "The one CAES plant we have in the United States is in Alabama; it is a 110-MW facility based on a unique design involving storage of the compressed air in an underground salt cavern. Now there are alternative designs that should allow us to deploy smaller CAES plants in 1 to 3 years. We can use standardized machinery for these units—a standard compressor and gas turbine—with installation either above or below ground. Moving quickly would give us an opportunity to show that storage technology can work and to show how its use can increase the value of wind power," Mansoor says.

Storage will alleviate some but not all of the problems associated with intermittency. New transmission lines to connect remote renewables sites to the grid will change the topology and power flows in the region. Thus there will be a growing need for power electronics that will allow new control strategies for renewables integration. The RD&D plan calls for the application of advanced power-electronic devices for wind integration beginning in 2010. Protection schemes that shield intermittent generation assets from the effects of unexpected power flows will be needed by 2015. Longer term, the plan calls for a demonstration of a superconducting "supercable" by 2025 that can deliver both hydrogen and electricity and provide storage in remote wind applications. Similarly, it calls for the deployment of high-voltage dc cables for delivering power from offshore wind farms by 2030.

Improved control of intermittent generation will also require the development of modeling tools to forecast renewable output 24 hours ahead. Specifically, EPRI's RD&D pathway looks for new analytical tools by 2015 to optimize regulation, reserves, and load-following requirements in regions with high penetration of intermittent resources. These tools could be coupled with new visualization capability to give operators a real-time, wide-area geographic view of intermittent supplies and transmission loading. Advanced visualization tools are expected to be ready by 2020.

The infusion of new technologies into the smart grid over the next 20–30 years could potentially result in significant improvements in transmission and distribution efficiency. As Mansoor points out, "T&D losses currently amount to 7% of the power generated in the United States. If we could reduce these T&D losses by just 10%, the kilowatthour savings would equal all of the wind power generated in the United States today."

NEW NUCLEAR INSTALLATIONS

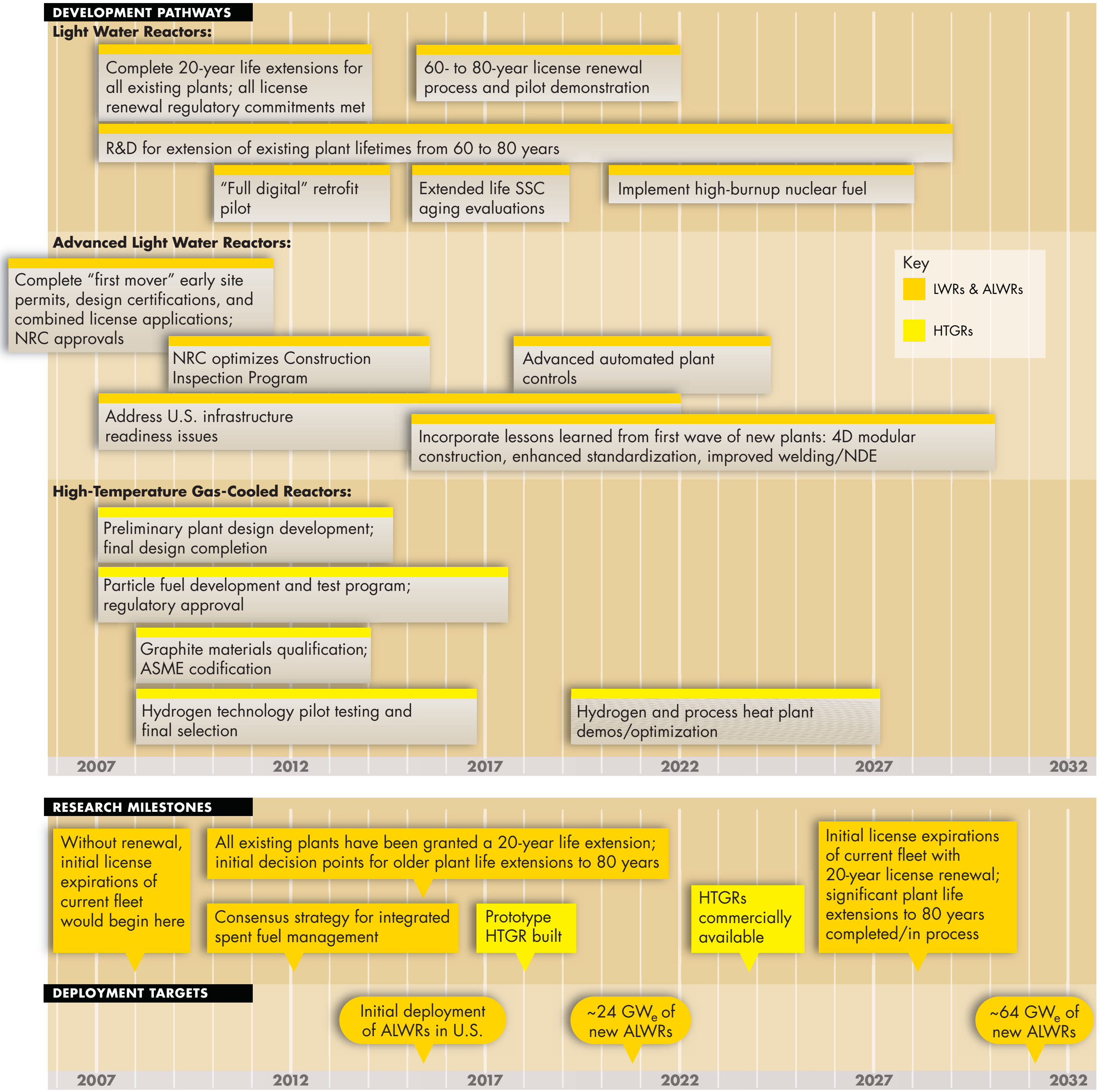
Nuclear power now accounts for 73% of the emission-free generation in the United States and is the only technologically mature, non-emitting source of power that is positioned to deliver large-scale CO_2 reduction in the decades ahead. EPRI's PRISM analysis assumes 64 GW of new nuclear by 2030—an ambitious but achievable target, according to Dave Modeen, vice president of the Nuclear Power sector: "The challenge ahead of us is to keep the current nuclear power plants running safely and reliably for 60 to 80 years, build out the next generation of plants starting around 2015, and achieve consensus on a long-term strategy for spent fuel."

The existing fleet of light water reactor (LWR) technology generates approximately 20% of the nation's electricity and operates at a capacity factor averaging 90%. This establishes a platform of confidence for the nation to proceed with further life extension of existing plants and to considerably expand the fleet using advanced LWR designs. Roughly half of U.S. operating plants have had their operating licenses extended from 40 to 60 years, and with a few exceptions, the remainder have applications in process or have filed letters of intent with the U.S. Nuclear Regulatory Commission (NRC).

> Nuclear's 90% capacity factor establishes a platform of confidence for the nation to proceed with life extension of existing plants and to expand the fleet using advanced designs.

The RD&D plan assumes that all units will be granted a 20-year life extension by about 2016, and it calls for the technical basis to be laid for an additional 20-year extension, from 60 to 80 years. EPRI is beginning discussions with DOE and the NRC to consider what it would take to establish this technical basis. "We believe that with sufficient maintenance, refurbishment, and upgrades, today's plants could operate quite safely for many more decades," says Modeen. "Ultimately, extending the life of our current fleet an additional 20 years will be a business decision, which means that both continued high safety performance and continued economic competitiveness must be addressed."

Critical technical milestones include assessing the ability of passive components, such as piping, civil structures, and power cabling, to perform safely over the extended period. In addition, plant economic performance goals and obsolescence issues will necessitate upgrading the instrumen-



tation and controls for all nuclear units to modern digital technology. Development of higher-performance fuels is another key goal; reliable high-burnup fuel would allow operators to extend the time between refueling outages while reducing the volume of spent fuel to be shipped and stored.

Two decades of investment in RD&D, including design development and prelicensing, have produced advanced light water reactor (ALWR) designs that are approaching “essentially complete design” status, which will enable new plant orders based on detailed cost and schedule estimates. There are five major commercial designs, two of which have been certified by the NRC and three of which are in process. ALWRs are already in operation today or under construction around the world—in France, Finland, Japan, Korea, and Taiwan. In the United States, over 15 companies have already stated their intent to file Combined Construction and Operating License applications with the NRC, for a total of about 30 reactor units. Most of the declared sites are those that were originally licensed to accommodate multiple nuclear units decades ago but that currently contain only one or two reactors.

The RD&D plan assumes the first commercial operation of ALWRs to begin in the United States by 2015. “The first new plants out of the box must be done very, very well,” says Modeen. “They must be executed thoughtfully, deliberately, and with the highest level of skill. I think none of us underestimate the challenge. Once that milestone is achieved, the industry must be prepared to sustain a much higher build rate in the years ahead if the PRISM deployment target is to be met.” Analysis with the economic model MERGE suggests an even more aggressive build rate out to 2050 and beyond.

The RD&D focus for new ALWRs is twofold: first, in the short term, to complete the engineering work necessary for detailed cost and schedule estimates for plant construction, and to resolve all remaining ALWR regulatory issues by 2011; and second, to begin now to lay the foundation for high build rates, so that strong, sustained expansion of ALWRs can proceed uninterrupted. This will include bringing capital costs and construction times down—for example, through expanded use of modular construction, advanced automated plant controls, and strict adherence to standardization. This effort will include addressing shortfalls in both physical and workforce infrastructure, such as the lack of forging capacity for large steel components, qualified N-stamp component suppliers, and qualified welders and welding inspectors. Local infrastructure issues requiring solutions include cooling-water access, environmental permitting, and transmission access. Most of these infrastructure challenges are generic to other generation technologies as well and will require the active engagement and leadership of federal and state government to resolve.

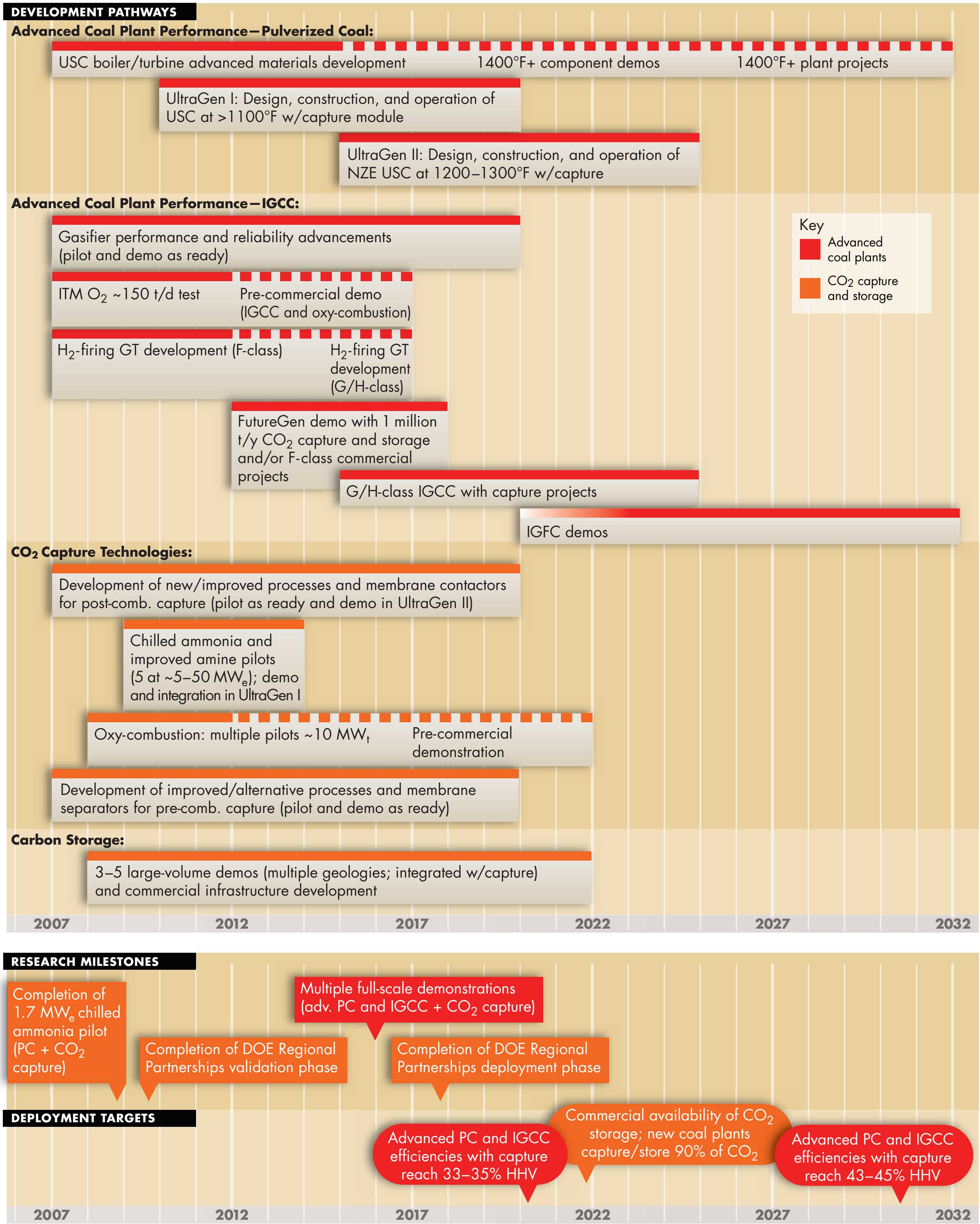
A related challenge for the industry is to help the U.S. federal government advance the capabilities of the High-Temperature Gas-Cooled Reactor (HTGR). Key milestones include construction of an operational prototype by 2018, enabling commercially available units by about 2025. The HTGR is particularly attractive for a carbon-constrained future because it could produce electricity, provide process heat for industrial applications, and also cost-effectively generate hydrogen by emission-free methods, using either catalytic processes or electrolysis of water. In a future hydrogen economy, the HTGR could provide clean energy for the grid, for industry, and for hydrogen fuel-cell vehicles. While DOE is directing the bulk of current R&D on this option and looking to the petrochemical industry as the primary investor in the technology, Dave Modeen believes that the power industry should play a role in HTGR development. “Given that the expertise to operate and maintain nuclear power plants really resides in the electricity sector, EPRI should help its members bring their operational and regulatory experience to the HTGR.”

Finally, sustained expansion of nuclear generation will ultimately require more work on spent-fuel management. On-site interim storage has operated safely and effectively for over 20 years and will be able to handle waste volumes until centralized interim storage is in operation. However, economic, security, and sustainability imperatives will require the establishment of an integrated fuel management system for the longer term. Such a system will include centralized interim storage, long-term geologic storage, and eventually, development of a closed fuel cycle, in which used fuel is recycled. To achieve these goals, a well-thought-out, deliberate consensus strategy on nuclear fuel storage—based on preliminary, laboratory-scale work—should be available by 2012. With this consensus, a comprehensive, closed fuel cycle that includes advanced reprocessing and separation technologies, reconditioning, fuel manufacturing facilities, and “fast” reactor technology would emerge around 2050.

ADVANCED COAL-BASED GENERATION

Sustaining coal as a viable option in a carbon-constrained world requires increasing the efficiency of coal-based generation while establishing the commercial reality of large-scale CO_2 capture and storage. EPRI’s technology pathway for coal aims at two critical targets. The first is to increase the efficiency of both pulverized-coal (PC) and integrated gasification–combined-cycle (IGCC) baseload plants with CO_2 capture to the 43–45% range by 2030. A 2% efficiency gain translates into a CO_2 emissions reduction of nearly 5%.

The second target: Ensure that coal plants built after 2020 can capture CO_2


DEVELOPMENT PATHWAYS
Advanced Coal Plant Performance—Pulverized Coal:
USC boiler/turbine advanced materials development
1400°F+ component demos
1400°F+ plant projects
UltraGen I: Design, construction, and operation of USC at >1100°F w/capture module
UltraGen II: Design, construction, and operation of NZE USC at 1200–1300°F w/capture
Advanced Coal Plant Performance—IGCC:
Gasifier performance and reliability advancements (pilot and demo as ready)
ITM O_2 ~150 t/d test
Pre-commercial demo (IGCC and oxy-combustion)
H_2-firing GT development (F-class)
H_2-firing GT development (G/H-class)
FutureGen demo with 1 million t/y CO_2 capture and storage and/or F-class commercial projects
G/H-class IGCC with capture projects
IGFC demos
CO_2 Capture Technologies:
Development of new/improved processes and membrane contactors for post-comb. capture (pilot as ready and demo in UltraGen II)
Chilled ammonia and improved amine pilots (5 at ~5–50 MW_e); demo and integration in UltraGen I
Oxy-combustion: multiple pilots ~10 MW_t
Pre-commercial demonstration
Development of improved/alternative processes and membrane separators for pre-comb. capture (pilot and demo as ready)
Carbon Storage:
3–5 large-volume demos (multiple geologies; integrated w/capture) and commercial infrastructure development
Key
🟥 Advanced coal plants
🟧 CO_2 capture and storage
2007
2012
2017
2022
2027
2032
RESEARCH MILESTONES
Completion of 1.7 MW_e chilled ammonia pilot (PC + CO_2 capture)
Completion of DOE Regional Partnerships validation phase
Multiple full-scale demonstrations (adv. PC and IGCC + CO_2 capture)
Completion of DOE Regional Partnerships deployment phase
DEPLOYMENT TARGETS
Advanced PC and IGCC efficiencies with capture reach 33–35% HHV
Commercial availability of CO_2 storage; new coal plants capture/store 90% of CO_2
Advanced PC and IGCC efficiencies with capture reach 43–45% HHV
2007
2012
2017
2022
2027
2032

from emission streams and that the CO_2 can be permanently stored. "The bottom line in coal," says Chris Larsen, vice president of the Generation sector, "is that we need to pursue multiple demonstrations of key technologies—advanced PC and IGCC systems, pre- and postcombustion capture, and CO_2 storage—in parallel, and we believe we are already late. We need to be working on this right now. There's a lot of activity already going on, but we need more, and we need it fast." Underlying Larsen's concern is the possibility that failure to adequately demonstrate capture and storage of CO_2 could prove to be a showstopper for coal in the coming decades.

Significant efficiency gains for PC technology can be realized only by increasing the peak temperatures and pressures of the steam cycle. Advanced materials such as corrosion-resistant nickel alloys will be necessary to accommodate these higher temperatures and pressures, as well as new boiler and steam turbine designs. It is expected that an advanced ultra-supercritical (USC) plant will be built during the next 7 to 10 years, following the demonstration and commercial availability of advanced materials from current research programs. Progressive research milestones include two proposed technical demonstrations: UltraGen I in 2020 and UltraGen II in 2025. UltraGen I will be a USC PC plant operating above 1100°F with 25–50% CO_2 capture. UltraGen II will be a more advanced USC PC plant—one with near-zero emissions (NZE) operating at higher temperatures (1200–1300°F) and with more than 50% CO_2 capture.

The prospects for IGCC improvements are also large. EPRI believes that by 2030, with aggressive RD&D, IGCC capital costs can be reduced by 30% while efficiencies are boosted to the 45% range (with CO_2 capture). Key technology advances include the development of larger gasifiers and the integration of these gasifiers with bigger, more-efficient combustion turbines. Ion transfer membranes and/or other low-energy-demand technologies are expected to significantly reduce the cost of oxygen supply for the IGCC process. By 2012, field testing of ion transfer membranes should lead to precommercial testing of IGCC with oxy-combustion technology. A key milestone target for around 2012 is the successful demonstration of FutureGen—an IGCC facility with the capability to capture and store up to 1 million metric tons/year of CO_2. By 2030, a subsequent demonstration of gasification technology integrated with fuel cells (rather than with combined-cycle combustion) should drive efficiencies well above the 50% range.

Failure to adequately demonstrate capture and storage of CO_2 could prove to be a showstopper for the continued use of coal in the coming decades.

Carbon capture and storage technologies can be integrated with virtually all types of coal-based generation, including IGCC, PC, circulating fluidized-bed combustion, and variants such as oxy-fuel combustion. An important technical distinction among these approaches is whether the capture is accomplished before or after combustion. Precombustion CO_2 separation processes suitable for IGCC plants are already used commercially in the oil, gas, and chemical industries at a scale close to that ultimately needed for power production. Currently, adding CO_2 capture, drying, compression, and transportation capabilities to IGCC plant designs would increase their wholesale cost of electricity by 40–50%. Advanced membrane technology to separate the CO_2 from a plant's synthesis gas may have the potential to lessen the cost-of-electricity penalty through reductions in both capital cost and auxiliary power requirements of as much as 50%.

Postcombustion CO_2 capture for PC plants uses a solvent to absorb CO_2 from the plant's flue gases. The current monoethanolamine process would reduce the plant's net power by nearly 30% and raise its cost of electricity by 65%. As a result, extensive research is under way to develop better solvents, such as chilled ammonia, which could reduce the power penalty to as low as 10%, with an associated cost-of-electricity increase of only about 25%. A 5-MW pilot-scale test of the chilled-ammonia solvent process at the We Energies Pleasant Prairie plant is now moving forward. "The concrete for the facility is being poured as we speak," says Larsen. "It's a partnership between EPRI, EPRI's members, and Alstom. The objective is to have the pilot operating later this year and into next year to support further scale-up of this promising technology."

Permanent storage of CO_2 is expected to be at least as challenging as its capture. Geologic CO_2 capture has been proven effective by nature, as evidenced by the many natural underground CO_2 reservoirs in Colorado, Utah, and other western states; CO_2 has also been locked away for millions of years in natural gas reservoirs. Large-scale injection and storage of CO_2 produced from electricity generation, however, has not been proven. DOE's active R&D program—the Regional Carbon Sequestration Partnerships—is mapping geologic formations suitable for CO_2 storage and conducting pilot-scale CO_2 injection validation tests across the country.

Following successful pilot projects, the partnerships will undertake larger demonstration projects in a variety of geologies, injecting quantities of 1 million metric tons or more of CO_2 (representative of typical annual coal plant emissions, which are on the order of 3–4 million metric tons) over several years and conducting postinjection monitoring to track the CO_2 plume and to check for potential leakage. The key RD&D milestone for 2020 is to have three to five large-scale demonstrations receiving captured CO_2 from local generating plants and injecting it for storage. Concludes Larsen, "If we really want the ability to capture 90% of the CO_2 from all new coal plants coming on-line after 2020, we will need a very aggressive RD&D program."

Steve Specker, EPRI CEO, sums up what is at stake. "We can't fumble the ball on CO_2 storage. There is no such thing as interim storage for CO_2, because the quantities we will be dealing with are so vast. If we miss, then these significant investments in advanced coal plants with CO_2 capture are not going to be utilized. We've got to make sure we get this one right."

LAUNCHING AND SUSTAINING A COMPREHENSIVE ACTION PLAN

Meaningful reduction in CO_2 emissions by the electricity sector demands a sustained, multi-decade RD&D program. This will require well-coordinated, collaborative programs involving both the public and private sectors. Although advances are needed all along the RD&D chain—in basic science, applied research, development, and demonstration—a significant portion of the activity will consist of large-scale demonstration projects. These must address key engineering issues and promote technology deployment strategies that are viable under financial and regulatory constraints.

EPRI estimates that pursuing all of the electricity technology RD&D pathways will require public and private investments in electricity RD&D, beyond those already being made, of roughly $1.5 billion a year for the next 25 years. Revis James, Director of EPRI's Energy Technology Assessment Center, emphasizes the urgency of resolute action. "The electricity sector will need these advanced technologies to successfully and efficiently operate under the CO_2 emissions reduction policies expected to be in place in the next few decades. With lead times of 20 to 30 years for technology development and deployment, it is essential to launch these technology pathways immediately."

This article was written by Brent Barker. Background information was provided by Revis James (rejames@epri.com) and Steve Gehl (sgehl@epri.com).

Revis James is director of EPRI's Energy Technology Assessment Center, which focuses on identifying strategic R&D priorities for the electric power industry, with special attention to options for CO_2 emissions reductions. Previously, he served as manager of EPRI's technology innovation program and managed programs on instrumentation and diagnostics and on maintenance optimization in the Institute's Nuclear Power sector. Prior to joining EPRI in 1992, James managed engineering design projects at Bechtel, ABB Impell, and ERIN Engineering and Research. He holds BS degrees in nuclear engineering and electrical engineering/computer sciences and an MS in nuclear engineering from the University of California, Berkeley.

Steve Gehl, technical executive for EPRI's Energy Technology Assessment Center, previously served as director of strategic technology with responsibility for EPRI's roadmapping and scenario planning efforts. He came to the Institute in 1982 from Argonne National Laboratory, where he was a staff metallurgist. Gehl received a bachelor's degree in metallurgical engineering from the University of Notre Dame and a PhD in materials science and engineering from the University of Florida.

Products & Services

Technology and expertise packaged for immediate use

Red Book Transmission Seminars: Learning From the Experts

Participants at a popular series of EPRI seminars are learning key theories and principles of overhead transmission from the experts who literally wrote the book on transmission line design, operations, and maintenance. In addition to classroom instruction, the weeklong seminars offer participants hands-on field experience with cutting-edge equipment and a chance to see, hear, and feel the high-voltage phenomena covered in the lectures. The response to the seminars has been so positive that EPRI is scheduling additional sessions at its Lenox facility in Massachusetts and at other EPRI locations and utility facilities in the United States and abroad.

"Transmission companies are caught in a time crunch between bust and boom," says EPRI's Andrew Phillips, transmission program manager. "After a prolonged drought in new line construction, the industry is entering a new era of transmission expansion worldwide—just as many veteran transmission engineers are retiring. Meanwhile, technology and practices have advanced since the boom years of the 1960s and '70s. Now new generations of engineers need to absorb the veterans' experience and also acquire proficiency with the latest tools so they can create new transmission infrastructure for the future."

Essential Transmission Reference

The seminars are based on the extensively updated new edition of EPRI's landmark overhead transmission reference, *EPRI AC Transmission Line Reference Book: 200 kV and Above, Third Edition* (EPRI Product 1011974). Originally printed in 1975 with a bright red cover, the publication quickly became known as the EPRI Red Book. Just as quickly, it became the worldwide industry standard reference for transmission line design. For more than 30 years, transmission engineers around the globe have turned to the Red Book to confirm design parameters, select technology, optimize designs, defend decisions, and bone up on nonroutine topics.

The new version significantly expands upon previous editions. In collaboration with member utilities, EPRI assembled a team of global experts to upgrade the guidebook to keep pace with technological advances and make the book truly international in its scope and content. The team updated eleven chapters and added four new ones to cover the full spectrum of overhead transmission topics, from fundamental concepts through insulation coordination, corona and field effects, and applications; of particular value is a new chapter on lines designed to operate above 700 kV.

The hard-cover text is supplemented by a CD-ROM containing more than 50 small software programs, called applets. These software applications incorporate useful help files, simple input and output screens, and the ability to export results to spreadsheets and graphs. The applets breathe life into the theories and principles described in the Red Book to increase the reader's understanding and reduce the effort necessary for implementation. The inclusion of graphing allows the reader to see precise results as well as trends.

Field Activities Complement Classroom Instruction

As a seminar text, the updated Red Book is proving as valuable a training tool as it is a reference for practicing engineers. The seminars introduce attendees to the book's diverse subjects, which are expanded in lectures delivered by many of the experts who wrote the topical chapters. In addition to Phillips, the expert authors include Bernie Clairmont and George Gela of EPRI, Luciano Zaffanella, Dale Douglas, Jim Stewart, Vern Chartier, and Chris Engelbrecht, among others.

The week-long seminars are being offered at various venues, including EPRI's Lenox High-Voltage Test Facility, at EPRI regional centers, and on-site at individual utilities, where course content is tailored to a company's specific needs and transmission system. Classroom instruction is structured around the Red Book's three general themes: insulation selection and coordination, corona and field effects, and application.

"Utilities have diverse and extremely talented workforces, but today people are so focused on their job responsibilities that many never have an opportunity to expand their understanding of the transmission system," says Eric Engdahl, principal engineer at American Electric

Power. “Attending a Red Book seminar may not immediately make them subject matter experts, but it will significantly increase their knowledge and broaden their perspective on what it means to be a utility engineer.”

The highlight of the seminar is the field day, where small groups of attendees participate in hands-on training and demonstrations to obtain real-life experience with high-voltage phenomena, tools, and techniques. At one station, attendees not only measure electric and magnetic fields using various meters but also experience sparking and the physical sensations associated with electric fields—such as skin tingling—bringing the previous day’s classroom lecture to life. At another station, attendees view corona using EPRI’s daytime corona camera and listen to the phenomenon using ultraprobes that amplify audible signals. Other demonstrations include switching surges, insulator design and maintenance, and measurement and mitigation of induced voltage on a mockup of a residential gutter system.

EPRI’s Lenox center has an array of full-scale transmission structures and high-voltage equipment to give students a real-world preview of what they might encounter in the field. “The EPRI test center is the perfect place to refresh or increase knowledge of high-voltage transmission line design and operation,” says Anne Bartosewicz, a transmission project director at Northeast Utilities. “One of the best parts of the class is the field day; the hands-on training provides practical exposure to the concepts discussed during class lecture.”

Although the training seminars are targeted for practicing transmission engineers, AEP and other utilities use the course to expand the knowledge of civil and mechanical engineers and even non-engineering personnel. At a recent seminar held at AEP facilities, attendees included staff involved in asset management, planning, and finance—all of whom gained valuable understanding of transmission fundamentals that will benefit the company as it expands its transmission network.

Future Seminars

EPRI is conducting fall seminars at American Electric Power (AEP’s second) and Southern Company. In 2008, EPRI will offer a spring regional seminar in the southeast and a summer seminar at its Lenox facility in Massachusetts. The Institute is also in discussion with three utilities—two of them international—for delivering in-house seminars in 2008.

For more information, contact Andrew Phillips, aphillip@epri.com, 704.595.2234.

EPRI Power Delivery Reference Books: Continuing a Colorful Tradition

For over 30 years, EPRI has been developing a series of comprehensive reference books—each with a distinctively colored cover—that document and distill the knowledge and experience of the world’s top power delivery experts. To capture the latest technical developments and practices in transmission, distribution, and power-flow-control engineering, EPRI is updating and expanding its library of power delivery reference books and developing much-needed new titles.

Now Available

Red Book *EPRI AC Transmission Line Reference Book: 200 kV and Above, Third Edition* (1011974).

Orange Book *EPRI Transmission Line Reference Book: Wind-Induced Conductor Motion* (1012317). Areas covered include aeolian vibration, conductor fatigue, conductor galloping, and wake-induced oscillation, with new chapters on fiber-optic cables and their associated aerodynamic problems.

Yellow Book *EPRI Overhead Transmission Inspection and Assessment Guidelines* (1012310). This reference provides guidance on establishing and refining inspection and assessment programs, with emphasis on asset management.

Green Book *EPRI Underground Transmission Systems Reference Book* (1014840). Issued in 2007, this new edition reflects the latest technology, new materials and methods, recently issued standards and regulations, and current utility needs and practices. New chapters have been added on hydraulic design and on grounding and cathodic protection.

White Book *EPRI Power System Dynamics Tutorial* (1001983). A comprehensive overview of power system dynamics, this tutorial provides the knowledge that operators will need to exercise critical judgment in emergency situations that fall outside the scope of step-by-step utility procedures.

In Development

Blue Book *EPRI Transmission Line Reference Book: 115–138-kV Compact Line Design* (December 2007).

Gold Book *EPRI Power Electronics–Based Transmission Controllers Reference Book* (2008).

Grey Book *EPRI Overhead Transmission Grounding Guide* (2008).

Brown Book *EPRI Underground Distribution Reference Guide* (2009).

Technology at Work

Member applications of EPRI science and technology

Roll Expansion Repair Technique Gains ASME Approval

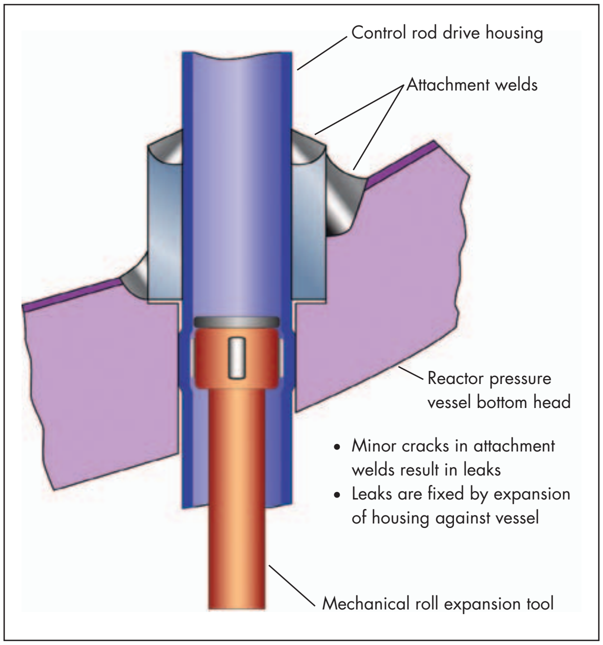
Age-related materials degradation can cause boiling water reactor (BWR) plants to develop cracks in control rod drive housing penetrations at the bottom of the reactor vessel. While the resulting leakage may be minor, it cannot be tolerated. Unfortunately, weld repair in these hard-to-access locations is extremely costly and time consuming. A safe and cost-effective repair technique could provide BWR owners with insurance against extremely costly weld repairs or more-invasive replacement projects that require prolonged outages.

One repair technique seen as having great potential for dealing with this problem is roll expansion, developed in the 1980s and applied successfully at Nine Mile Point Unit 1 to seal bottom head penetration leakage. The technique involves inserting a mechanically expanded roller assembly into the control rod drive housing from under the reactor vessel. Increasing the diameter of the roller assembly as it rotates increases the inside and outside diameters of the housing, sealing the small gap between the exterior tube wall and the reactor vessel bottom head, thereby eliminating the leakage.

Some years ago, EPRI, in collaboration with the BWR Vessel and Internals Project (BWRVIP, an international association of utility BWR owners), developed a technical basis for generic application of the roll expansion repair and submitted it to the Nuclear Regulatory Commission. The NRC did not, however, approve the procedure for generic use at all plants, because reactor vessel repairs fall under the jurisdiction of the American Society of Mechanical Engineers (ASME). For BWR utilities to apply this safe and economical alternative to costly weld repairs, the procedure had to receive ASME Code approval.

In pursuit of this goal, EPRI formed a focus group within the BWRVIP to develop the overall project plan and then initiated the analyses and testing necessary to support the technical justification for this application of roll expansion. Under the leadership of Exelon's Greg Harttraft, the group assembled a body of technical information to support approval under the ASME Code. The effort included detailed fracture mechanics analysis to evaluate the structural consequences of the cracking; metallurgical assessment; and extensive testing to determine the load capability and sealing effectiveness of the roll repair joint.

The testing was conducted at Nuclenor S.A. facilities in Spain under the direction of Fernando Corchon. Full-scale roll repair mockups were used to simulate field conditions and assess the mechanical strength of the repair. Results showed substantial load capability and established that the roll joint is not only a leak barrier but a structural load–carrying joint as well. As part of the Nuclenor work, the project team also developed specific procedures for performing roll expansion repairs.



Armed with the project team's results and EPRI technical support, Harttraft spearheaded the development of ASME Code Case N-730 and worked with ASME subcommittees to develop a consensus on the technique. These efforts paid off with ASME Code approval of the technique as a permanent repair option for addressing leakage in control rod drive housing penetrations in BWRs.

ASME Code approval means BWR owners around the world can now use the roll expansion technique if their units develop cracking and leakage. Because the problem area is accessed from under the reactor vessel, repairs can be made without interfering with other operations and with no need for special actions such as offloading the core or draining the vessel. This means that roll expansion can be performed during a regular refueling outage.

According to Exelon's Harttraft, the advantages offered by the new technique are substantial. "Repairing a leaking housing using the roll expansion technique costs only about one-tenth as much as other methods of repair," he says. "In addition to the factor-of-ten cost savings, roll expansion can significantly reduce facility downtime and personnel radiation exposure."

Additional work is now under way to develop revisions to the ASME Code Case to include roll expansion for in-core monitor housing penetrations. Upon completion of this activity, the code case will encompass all BWR bottom head penetrations.

For more information, contact Robert Carter, bcarter@epri.com, 704.595.2019.

NYPA Applies Probabilistic Risk Assessment for Power Reliability

Ensuring the reliable delivery of electricity is the primary challenge facing power system operators and planners. In today's restructured power industry, many transmission systems are stretched to their limits to accommodate interregional bulk power transfers they were never designed to handle. Meanwhile, customer expectations of reliability are increasing, and the consequences of power outages have never been greater. Even small weak points in the power delivery system, if undetected and uncorrected, might eventually lead to costly outages or trigger cascading failures that affect large regions.

Like other electricity providers, New York Power Authority (NYPA) has a strong commitment to supplying its customers with a reliable supply of economical power. To maintain that commitment into the future, NYPA's transmission planners must address an array of uncertainties. These include lack of clarity in the location, timing, capacity, and availability of future generation and transmission facilities; concerns over the timing and complexity of wholesale power transactions; and questions about the characteristics of future loads.

In such an uncertain environment, the traditional methods of performing power system reliability assessments are no longer adequate, largely because they use a deterministic approach to calculate the impact of potentially disruptive events, without regard to the probability of their occurrence. NYPA sought a new approach that quantifies both the risk of system contingencies and their physical impact.

NYPA worked with EPRI to apply an advanced methodology, Probabilistic Reliability Assessment (PRA), to perform a risk assessment study of the New York State power system. Developed under EPRI's Transmission Reliability Initiative, the PRA program provides a more accurate tool for assessing grid reliability under restructured market conditions. Unlike traditional deterministic contingency analysis tools, PRA calculates a measure of the probability of undesirable events, along with a measure of their severity or impact. It also allows grid planners to assess the tradeoffs between the probability of a contingency's occurrence and the cost of mitigation.

To enhance applications of the PRA methodology, EPRI internally developed the Probabilistic Reliability Indices (PRI) program as a tool for system operators and planners to use in performing risk-based assessments. The PRI program uses contingency analysis results as well as equipment outage information as inputs to compute probabilistic reliability indices. The program also allows users to perform a variety of analyses that provide a more robust understanding of the reliability situation, including overall analysis, interaction analysis, situation analysis, root cause analysis, and weak point analysis.

Pei Zhang and Liang Min of EPRI worked with Liana Hopkins, senior system planning engineer with the Operations Planning Group at NYPA, on the risk assessment study of the New York power system, with particular focus on NYPA's transmission network. The collaborative PRA study produced a number of beneficial results:

- assessment of overall system reliability
- clarification of the cause-and-effect relationships among user-defined areas
- ranking of the contingencies according to their contribution to reliability indices
- identification of the transmission system components most likely to contribute to critical situations
- identification of the specific branches and buses most susceptible to interruption

The study provided NYPA system planners with complementary information in the form of charts, tables, and maps, helping them process both the details and the big picture of the complex reliability equation. NYPA's Liana Hopkins comments on this comprehensive perspective: "The PRA methodology is extremely valuable in helping system planners visualize their system reliability and its interaction with neighboring areas. PRA can pinpoint the critical contingencies that have both high probability and high impact; in this way, planners can monitor weak spots more closely during system operation and are more likely to develop effective remedial schemes when problems do occur."

The NYPA project demonstrates that the PRA methodology offers power providers greater accuracy under conditions of uncertainty. In addition, it helps planners identify the most critical potential grid failures, evaluate their impacts, and develop effective mitigation alternatives. For the future, PRA can assist transmission planners in creating more-robust system designs and can help decision makers prioritize transmission projects. Moreover, PRA provides opportunities to integrate planning and operation functions more closely, to the benefit of both areas.

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BWRVIP-176: BWR Vessel and Internals Project, BWR Shutdown Chemistry Experience Report and Application Guidelines
1014999 (Technical Report)
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BWRVIP-87, Revision 1: BWR Vessel and Internals Project, Testing and Evaluation of BWR Supplemental Surveillance Program Capsules D, G, and H
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