SUMMER 2007

EPRI JOURNAL

ELECTRIC POWER RESEARCH INSTITUTE

Renewables

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.

Together. . . Shaping the Future of Electricity®

EPRI Journal Staff and Contributors
David Dietrich, *Editor-in-Chief*
Jeannine Howatt, *Business Manager*
Debra Manegold, *Layout Designer/Production Manager*
Ken Cox, *Illustrator/Photographer*
Craig Diskowski, *Art Consultant*

Jeremy Dreier, *Senior Communications Manager*
Joseph Bugica, *Vice President, Marketing*
Henry A. (Hank) Courtright, *Senior Vice President, Member Services*

Contact Information
Editor-in-Chief
EPRI Journal
PO Box 10412
Palo Alto, CA 94303-0813

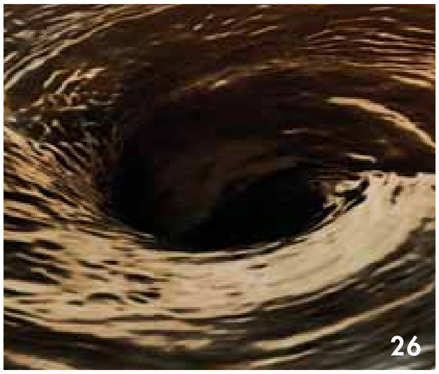
For information on subscriptions and permissions, call the EPRI Customer Assistance Center at 800.313.3774 and press 4, or e-mail journal@epri.com. Please include the code number from your mailing label with inquiries about your subscription.

Visit EPRI's web site at www.epri.com.

Cover art by Craig Diskowski/Edge Design.

EPRI JOURNAL

SUMMER 2007



EDITORIAL

2 Technology Tools: The Importance of a Full Tool Box

IN MEMORIAM

4 Chauncey Starr (1912–2007)

COVER STORY

6 Renewables: A Promising Coalition of Many

Wind, solar, biomass, and ocean energy options are largely unrelated technologically, each having its own discrete developmental and economic challenges. Understanding the place of these technologies in a clean, sustainable energy future requires an appreciation of their individual limitations and opportunities.

FEATURES

16 In Pursuit of a Nuclear Renaissance

Virtually every credible plan for dealing with climate change includes increases in the use of nuclear power. Advanced reactor designs are available to support such a resurgence, but getting new plants built will require substantial work on technical, regulatory, and business issues.

26 Running Dry at the Power Plant

Utility companies—which use substantial amounts of water for plant cooling and other needs—are adopting water-conserving technologies, innovative recycling schemes, and alternative sources of water to deal with growing difficulties in securing supplies of fresh water.

DEPARTMENTS

3 Contributors
36 Technology at Work
38 International

LISTINGS

39 Technical Reports and Software

Editorial

Technology Tools: The Importance of a Full Tool Box

At EPRI we believe strongly that our public interest mission is to provide society with a broad portfolio of technology options for generating, delivering, and using electricity in ways that are safe, reliable, affordable, and environmentally responsible. As we look to the future, this is best achieved through collaborative programs in research, development, and demonstration that will enable society to address such hugely important environmental challenges as global climate change and water sustainability.

This edition of the *Journal* includes articles on two important zero-carbon power generation technologies: renewables and nuclear power. Previous editions have covered such technologies as energy efficiency, advanced coal, carbon capture and sequestration, and plug-in hybrid electric vehicles (PHEVs). EPRI's recent Prism analysis (see www.epri.com) concludes that society will need all of the above-mentioned technologies to enable the electricity sector to meet the increasing demand for electric power, while slowing, stopping, and eventually reversing the projected increase in its CO_2 emissions.

But the electricity sector can do more than just reduce its own emissions. A two-volume report issued by EPRI this summer provides an environmental assessment of the impact of PHEVs on greenhouse gas (GHG) emissions and air quality in the United States. The study analyzed nine scenarios, in which PHEVs achieve a lesser or greater share of the U.S. vehicle market and the electricity sector achieves varying levels of CO_2 intensity. All nine scenarios result in net annual GHG emissions reductions—ranging from 4.5 billion tons to 14.5 billion tons of CO_2 equivalent by 2050.

This result should not be surprising. Numerous studies by EPRI and others have consistently shown that the tighter the cap on GHG emissions across the whole economy, the greater will be the percentage of electricity used, relative to other forms of end-use energy.

Water sustainability is an issue throughout the United States and in most areas of the world where population pressures are mounting. As one of the major users of water, the electricity sector must take a leadership role in developing new technologies that can help conserve this essential but limited resource. The article titled "Running Dry at the Power Plant" provides an excellent summary of the challenges and EPRI's collaborative programs to develop and help implement the needed technologies.

I stated at the beginning that it is EPRI's public interest mission to provide society with technology options. With technology needed to address everything from climate change to water sustainability, one size does not fit all. We need a diverse set of tools. Research in renewables clearly shows that various states, regions, and nations must have the flexibility to use those tools and resources that best meet their needs.

And now, PHEV research shows us that even the cars and trucks we drive can provide an important technology option—another tool for solving our energy and environmental challenges.

Society needs every technological tool at its disposal. Our job at EPRI is to help fill up the tool box!

SR Specker

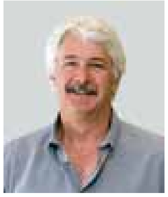
Steven Specker
President and Chief Executive Officer

To access the PHEV study on line, visit the EPRI web site (www.epri.com) and search by the following report numbers: 1015325 (effects on greenhouse gas emissions) and 1015326 (effects on air quality).

Contributors


KEY


BEDARD


O'CONNOR


MULFORD


VINE


GOLDSTEIN

Renewables: A Promising Coalition of Many (page 6) was written by science writer John Douglas with technical assistance from Tom Key, Roger Bedard, and Dave O'Connor.

Tom Key, technical leader for renewable and hydropower generation, started in 1989 at EPRI-PEAC, which became part of EPRI in 2005 with the restructuring of the Institute's subsidiaries. Previously he worked at Sandia National Laboratory, specializing in the compatible interface of end-use equipment and distributed power systems. Key earned a BS in electrical engineering from the University of New Mexico and an MS in electrical power engineering and management from Rensselaer Polytechnic Institute.

Roger Bedard leads EPRI's research on ocean energy and solar-thermal technology. He came to the Institute in 1997 from Alstom Robotics, where he served as vice president of program management, specializing in robotics applications for nuclear waste cleanup. Earlier he managed the Mars Rover and terrestrial solar-thermal electric programs at the Jet Propulsion Laboratory and managed business development for distributed solar receivers at Acurex Corporation. Bedard received a BS in mechanical engineering from the University of Rhode Island and an MS in the same field from UCLA.

Dave O'Connor, a senior project manager for combustion performance, heads the Institute's activities on biomass energy conversion. He joined EPRI in 1986, focusing primarily on fuels and asset management tools for fossil-fired plants. Earlier he worked for six years at Bechtel Group as a research engineer, providing analysis and testing services for coal-based energy ventures. O'Connor has a BS in mining engineering from the South Dakota School of Mines and Technology.

In Pursuit of a Nuclear Renaissance (page 16) was written by science writer Alice Clamp with technical information from Tom Mulford and Gary Vine.

Tom Mulford, manager of EPRI's Advanced Nuclear Technology (ANT) Program, is responsible for overall technical, administrative, and financial management, as well as strategic development and industry integration of ANT activities. He joined EPRI in 1991, having been previously employed by General Electric Nuclear and by NUTECH Engineers/International. Mulford has a BS in mechanical engineering from San Jose State University and has completed extensive postgraduate studies in the field.

Gary Vine, executive director for federal and industry activities in EPRI's Nuclear Sector, joined the Institute in 1981 to manage safety analysis and response at the Nuclear Safety Analysis Center. From 1987 to 1988, he served in Washington, D.C., as the first EPRI liaison to the Nuclear Management and Resources Council—a predecessor of the Nuclear Energy Institute. Earlier, Vine served for over 11 years in the U.S. Navy submarine program. He received a BS degree in physics and mathematics from the U.S. Naval Academy and an MS in physics from the U.S. Navy Postgraduate School.

Running Dry at the Power Plant (page 26) was written by science writer Brent Barker with technical information from Robert Goldstein.

Robert Goldstein is technical executive for EPRI's water and ecosystems research. He joined the Institute in 1975 to work on environmental/ecological issues. Goldstein previously worked for six years as a systems ecologist at Oak Ridge National Laboratory. In addition to a BA from Queens College, he has a BS in engineering and MS and EngScD degrees in nuclear science and engineering from Columbia University.

Chauncey Starr

1912–2007

EPRI lost its strongest advocate and most incisive and independent voice with the recent passing of Chauncey Starr, the Institute's founder. Chauncey died at home on April 17, the day after talking with many old friends and current colleagues at an EPRI event celebrating his 95th birthday. Although physically frail, he held the assembly rapt for several hours with sharp insights into the value and challenges of science and technology, strong opinions on the state of the world, and fascinating anecdotes from his colorful career. "Chauncey was a very rare individual—an inspiration to the staff and a sort of corporate conscience for us all," says EPRI president Steve Specker. "I've been fortunate to have his counsel in my time at EPRI."

The Early Years

Chauncey began his career in an academic setting, focusing on materials research at Harvard and MIT after earning his PhD in electrical engineering from Rensselaer Polytechnic Institute in 1935. His natural bent for practical application led him to several years with the Navy Department's Bureau of Ships, where he investigated ways to protect vessels from underwater mine explosions, and then to a key position with the wartime Manhattan Project. Working with E. O. Lawrence and J. Robert Oppenheimer, Chauncey directed the construction and operation of the calutron magnetic centrifuge, which was at the center of the government's uranium enrichment program.

After the war, Chauncey turned his attention to the use of nuclear energy for the betterment of society—a goal that remained a lifelong personal passion. In 1946 he started a 20-year tenure as general manager, head of research, and president of what became North American Rockwell's Atomics International division. He returned to academia in 1966 for 7 years as dean of the School of Engineering and Applied Science at UCLA. The formation of EPRI came next—a challenge that called on the entirety of his scientific, business, and leadership skills and secured his reputation as a visionary of the first rank.

Inventing the Institute

The great New York–Northeast blackout of 1965 had a chilling effect on the electric power industry. By 1971, in response to serious public concern about the long-term reliability of the U.S. electric power system, Congress was considering creation of a new federal agency to conduct electricity-related R&D, funded by a tax on kilowatthours sold. The industry, acting through its Electric Research Council (ERC), proposed its own alternative, charging Carolina Power & Light CEO Shearon Harris with finding someone capable of framing a formal, industry-funded electricity R&D program—someone Harris said would "need to be an internationally respected scientist with uncommon administrative ability." He found his man in Chauncey Starr.

But it wasn't Chauncey's resume, impressive though it was, that closed the deal; rather it was a succinct, three-page letter to ERC's selection committee in which Chauncey laid out a structure and philosophy for EPRI that defined its purposes, potentials, public status, and role in technology development and national planning. It was a vision that was stunning in both its details and its broadest ideals. Independence, complete objectivity, thoroughness, and intellectual integrity would be the foundation of the Institute's effectiveness. And far from constraining its focus to aiding equipment suppliers in their development of new hardware, as some had proposed, EPRI would deal with a scope of issues commensurate with the most wide-reaching concerns and benefits of the electricity enterprise, including environmental and social issues.

Chauncey's plan for how EPRI's research would be organized and administered was also unconventional, and far more ground-breaking and innovative than it may appear today. As David Saxe, EPRI's first director of administration, pointed out in a 1992 interview, "It was the first large industrywide R&D consortium anywhere in the world, and there just weren't any patterns to follow." One crucial issue was whether EPRI would have its own laboratories for conducting research—the standard model employed by GE, Bell Labs, and other industrial giants. Firmly believing that the most important asset of an effective research organization is its intellectual capital rather than its buildings and equipment, Chauncey opted instead for a "virtual" laboratory: EPRI would keep the intellectual activity under its control with its own staff, while the physical activity was contracted out. This plan not only avoided large capital costs but also allowed the Institute to tap the expertise of the preeminent experts in any technical field, anywhere in the world.

An Original Thinker

Attracting intellectual capital was one of Chauncey's particular talents, and he mentored dozens of colleagues, young and old, with a natural, informal style that inspired insight, innovation, and original thought. As one long-time co-worker put it, "Chauncey was thinking outside the box long before the rest of us knew there *was* a box." David Saxe was more specific: "He doesn't like structure, he doesn't like rules. Any time a rule gets in the way of accomplishing something he thinks is sensible or important, he is completely impatient with the rule—and with anybody who cites the rule rather than the objective. He just goes to the heart of the matter. He is the goal-oriented leader par excellence." Indeed, Chauncey's steadfast opposition to the constraints of convention echoed in his final words of advice the day before he died: "My simple guide, 'disregard all organization charts,' is my 95th-birthday legacy to EPRI."

RON MAY

While Chauncey's iconoclastic outlook goes a long way in explaining his creativity and inspirational powers, it alone does not account for the intellectual qualities people found most impressive—the clarity, incisiveness, and logical thrust of his thinking. As Starr protégé and later EPRI president Richard Balzhiser observed, "Chauncey has an exceptionally quick mind; he's better with half the facts than most people are with all the facts." The true power of his thinking, many believe, was not a matter of *what* he thought but of *how* he thought—a topic Chauncey himself weighed in on from time to time: "It is important for individuals and societies to have ways of filtering out wishful thinking, fantasies, and social myths. The way I do this is to not operate intuitively; I don't close my eyes and commune and wait for the right answer. I try to go back to fundamental principles and derive the answer through a series of analyses and evaluations of options. I don't accept other people's values per se. I want to know *why* the values are there, what their origins are, and what they mean, and then I accept those that make sense to me."

The Starr Legacy

The scope of Chauncey's interests was bounded only by the limits of his curiosity—which is to say, there were no boundaries at all. He published over 400 papers in his career on a tremendous range of topics: energy supply and demand, fuels and waste disposal, nuclear weapons proliferation, energy education policies, resource conservation, and national energy policy, to cite a few. A seminal 1969 article in *Science,* "Social Benefits versus Technological Risk," is widely considered to have crystallized the fundamentals of risk analysis as a basis for public policymaking.

His decades of important work brought Chauncey dozens of major awards and honorary affiliations, including the French Legion of Honor, the United States Energy Award, the National Medal of Technology, the American Physical Society's George E. Pake Prize, and the National Academy of Engineering's Arthur M. Bueche Award. But despite the opportunity to rest on these many laurels, Chauncey refused to do so. At 95, he was still in the office five days a week from ten o'clock until five or so, working on his next project, or as he put it, "my current four projects." One of these, the SuperGrid, is a fundamental rethinking of the U.S. electric power generation and delivery infrastructure, involving superconducting electricity transmission, hydrogen production and distribution, and a coast-to-coast backbone of advanced subterranean nuclear power plants.

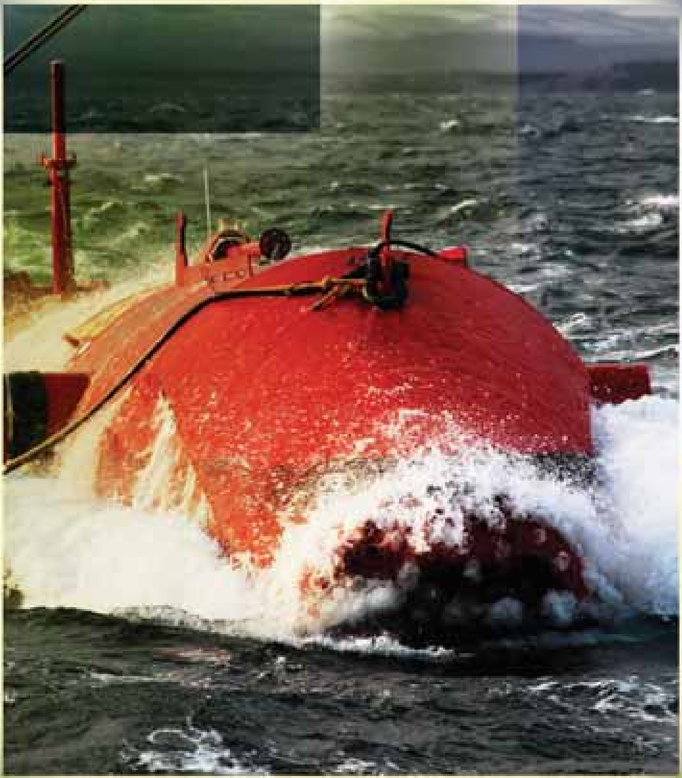
The SuperGrid is a concept that Chauncey knew he would never live to see built, but as a staunch believer in the long view, he wasn't bothered a bit: "An individual, or a generation, involved in creative activity may get immediate pleasure from it," he said, "but the real benefits flow to the succeeding generations. The only justification for society's supporting R&D is to make the world better for the future—to create an intellectual or technological endowment for our children and their children."

Renewables:

A Promising Coalition of Many

The Story in Brief

Renewable energy technologies are most often spoken of and considered collectively. But wind, photovoltaic, solar-thermal, biomass, tidal, and wave energy options are largely unrelated technologically, each having its own discrete developmental and economic challenges. Understanding the place of these technologies in a clean, sustainable energy future requires an appreciation of their individual limitations and advantages and a familiarity with the expectations for advancements over the next two decades.



UNDERWATER TURBINE PHOTO COURTESY VERDANT POWER, INC.
PELAMIS WAVE ENERGY CONVERTER PHOTO COURTESY OCEAN POWER DELIVERY LTD.
WOOD CHIP PILE PHOTO © MAX BLAIN/DREAMSTIME.COM

Wind power is now competitive with conventional electricity generation in favorable locations. Much of today's research is focused on dealing with the intermittency of the wind resource and integrating often-remote installations into the power grid.

The importance of renewable energy resources has been recognized—and repeatedly rediscovered—since ancient times. By the first century, waterwheels were driving the bellows of blast furnaces to create cast iron in China, and the Greek engineer Hero had described a wind-powered organ. Archimedes reportedly used solar energy concentrated by mirrors to set Roman warships afire during the siege of Syracuse in 212 BC, and in 1839, a very young Edmund Becquerel discovered the photovoltaic effect. Even the Model T car was originally designed to run on either ethanol or gasoline, and Henry Ford actually constructed an ethanol fermentation plant to supply the fuel.

So why aren't we using more wind, solar, and biomass energy today? And what role are such renewable resources likely to play in the future? The answers to such questions are as diverse as the resources themselves—a group of largely unrelated technologies now being considered together because of their potential importance in helping limit carbon dioxide (CO_2) emissions, which contribute to global warming, and in reducing America's dependence on imported oil. As those concerns become more urgent, the drive to deploy nonemitting energy resources is accelerating rapidly, but success will depend on a wide variety of individual technology development paths.

Estimates of the contribution renewables will make to our energy future have been made by many different organizations, and the results vary widely, depending on the studies' assumptions and modeling approaches (see sidebar, p. 10). Still, one premise common to all estimates is that substantial research and development efforts will be needed in order for renewables to compete economically with other energy sources, such as nuclear power and coal plants with CO_2 capture and storage. In some cases, such as wind, the main problem is how to integrate an inherently intermittent resource into an electricity grid whose supply and demand must remain balanced within seconds and within very narrow voltage and frequency limits. Reducing costs will be the primary issue for photovoltaics, with several potential breakthroughs already being explored. And for biomass, fundamental questions remain about what approach to follow and which fuel stocks to use.

Wind: Tackling Barriers to Grid Integration

With installed capacity in the United States of more than 11 GW and annual growth rates estimated by the American Wind Energy Association at more than 25% a year, wind energy continues to dominate renewable energy additions to the electricity generation mix. Indeed, for the last two years, wind has ranked second only to natural gas in terms of contributing new generating capacity. Much of this growth has been driven by steady improvements in generation technology, which have made the cost of electricity from wind resources competitive with that from fossil fuels in an increasing number of circumstances, both in this country and worldwide. Two inherent barriers remain, however, to the large-scale integration of wind energy into utility networks: the remoteness of many windy areas, and natural fluctuations in the wind resource in even the best locations. Recent progress has been made in addressing both of these problems.

Carrying power to load centers from wind farms in remote areas often requires construction of new transmission lines. Under previously common regulations, the addition of such lines raised a classic chicken-or-egg problem: typically, wind facilities weren't built unless connection with potential markets was assured, but the necessary power lines tended not to be added unless wind farms were already in place. Specifically, in California, power plant owners were required to pay all the costs of connecting new plants to the grid, which created a particular burden for small wind farms. To resolve this dilemma, the California Independent System Operator—with support from the California Public Utilities Commission and the nongovernmental Natural Resources Defense Council—requested the Federal Energy Regulatory Commission (FERC) to allow shifting part of the cost to consumers. In

January 2007, FERC issued a unanimous decision saying that plant owners should pay for their share of the line but that all power consumers would assume the costs of unused line capacity until the capacity was fully subscribed.

The use of backup power or energy storage can substantially reduce the problems that resource intermittency brings to integrating wind into the power grid, but both of these options are relatively expensive today. To address the wind variability issue more cost-effectively, EPRI has been working with the California Energy Commission to develop and test regional and wind plant–specific wind energy forecasting systems that will allow better coordination of wind resources with a utility's other generating options. The recently completed project addressed both same-day and next-day hourly forecasts of wind speed and energy generation for the principal wind resource areas of California. Especially in regions with large concentrations of wind generation facilities, accurate forecasts are needed both to support green power markets and to assist system operators as they adjust other generation and transmission resources to follow load. In future work, EPRI is planning to implement the new algorithms in a real-time wind forecast workstation.

Meanwhile, the National Research Council—the research arm of the U.S. National Academy of Sciences—has published a report, *Environmental Impacts of Wind Energy Projects,* that proposes guidelines for evaluating the trade-offs between the benefits of new projects and their potentially negative impacts on the environment. Of particular concern is the death of birds and bats from collisions with the spinning blades. The report concluded that, at the current level of U.S. installed wind capacity, there is "no evidence of significant impacts on bird populations," with the possible exception of certain raptors that collide with older wind energy machines in one area of California. Nevertheless, the report recommends development of a more-extensive knowledge base that regulatory agencies can use to evaluate potential problems—an effort that would entail more-careful tracking of bird and bat populations to assess behavior, migration corridors, and other factors that could affect the risk of collisions.

Solar-Thermal Power: Renewing the Promise

Solar-thermal electricity (STE) is back. In spite of successful demonstrations of various STE technologies in the 1980s and early 1990s, the idea of concentrating solar power to heat a working fluid and generate electricity with a turbine or engine was largely ignored during the turbulent era of energy industry restructuring.

That has now changed, and more than a gigawatt of STE central station power plants are now in various stages of planning and early construction around the world. This shift is due not only to altered circumstances but also largely to the recognition that in multi-megawatt plants, STE provides the lowest-cost solar electricity available today. Advances in key plant components, as well as parallel advances in materials science, thermal storage, and computerized controls, have reduced the wholesale cost of electricity to close to 10¢/kWh for a large STE plant under the most favorable circumstances (see Further Reading, EPRI Report 1012731). Additional cost reductions are expected from plant scale-up and increased component production volume.

Actually, STE never entirely went away. The 354-MW Solar Energy Generating Station (SEGS) in California's Mojave Desert—built in stages—has been providing electricity for roughly two decades and is still the world's largest solar power plant. This facility uses long, trough-shaped mir-

Parabolic trough systems are considered the most reliable and least costly of today's solar-thermal electricity (STE) technologies. The Nevada Solar One plant—a 64-MW installation that lines up 760 parabolic concentrator arrays—began generating power in June. (photo: Acciona Group)

Sandia National Laboratories is evaluating solar dish–Stirling STE systems at its National Solar Thermal Test Facility in Albuquerque. The dish units, which are automated to track the sun, concentrate heat on a Stirling engine, which drives an electric generator. (photo: Randy Montoya)

Estimating Future Renewable Generation

While the technical capabilities of renewables and their contribution to the electricity generation mix are both growing steadily, estimating how much growth will be achieved—and by when—remains extremely difficult. Many uncertainties could affect the outcome, including possible mandatory restrictions on carbon dioxide emissions, introduction of a federal renewable portfolio standard (RPS), variations in fuel prices, offerings of deployment incentives, and changes in the rate of demand growth. The projections of renewable generating capacity presented in this article represent an assessment of current trends and expected technical potential, not predictions of what will actually happen in the future.

The following table, which compares estimates drawn from several sources and based on a range of assumptions and modeling approaches, illustrates the point. The NEMS model, produced by DOE's Energy Information Agency (EIA) and published in its *Annual Energy Outlook* (AEO), provides a baseline projection of 40 GW of additional renewable capacity by 2030 under a business-as-usual scenario that assumes no major changes in government requirements or incentives.

EPRI's technical feasibility estimates for CO_2 reduction (Prism model) also exclude external economic factors but assume substantial research and development activities and a balanced portfolio of high-tech generation technologies; under these assumptions, the analysis projects a possible 70 GW of new renewable capacity by 2030. Another EPRI assessment, based on the National Electric System Simulation Integrated Evaluator (NESSIE) model, considers the effects of fuel prices and CO_2 costs in its analysis; NESSIE projects a renewables capacity of 155 GW if natural gas prices are high and CO_2 constraints are imposed on electricity.

The NESSIE projections are relatively close to the projections for a 15% federal RPS. In contrast, significantly higher estimates come from renewables advocacy groups; their assessments were recently published in *Outlook on Renewable Energy in America*, from the American Council on Renewable Energy (ACORE). This outlook assumes the practical use of a very large portion of the country's natural renewable assets, focusing on the abundance of the resources rather than on technical and economic constraints.

Source of Estimate	Description of Estimate	Target Year	Renewable Capacity (GW)	Renewable Energy (TWh)	Method/Conditions/Assumptions
EIA AEO 2007	NEMS model	2030	40	177	Calculated from economic supply-demand model, no CO_2 tax, business-as-usual scenario
EPRI CO_2 Prism	Technical feasibility	2030	70	307	Estimates technical potential for renewables to reduce CO_2 emissions from electricity industry; no CO_2 tax
EPRI Renewable Energy Scenarios	NESSIE model	2030	155	737	Calculated from economic supply-demand model, with high CO_2-cost and gas-price scenarios
Calculated from demand	Federal RPS of 15%	2030	177	775	Simple multiplication of RPS by expected electricity sales or demand from AEO 2007
Calculated from demand	Federal RPS of 25%	2030	295	1292	Simple multiplication of RPS by expected electricity sales or demand from AEO 2007
ACORE *Outlook on Renewable Energy*	Resource availability	2025	635	1947	Assumes significant renewables deployment and incentives to bridge the cost gap

Notes:
Renewable capacity excludes conventional hydropower.
EIA and EPRI use a 50% capacity factor to convert between energy and capacity.

rors with a parabolic cross section to focus sunlight on receiver tubes filled with synthetic oil. This heat transfer fluid is pumped through a series of heat exchangers to produce superheated steam that powers a conventional turbine-generator. Natural gas can be used to provide up to 25% of the system output, enabling the system to generate dispatchable power when solar energy is not available.

Largely because of this experience, parabolic trough systems are considered the least expensive, most reliable STE technology for near-term deployment, and several new projects are under way. The Nevada Solar One plant, for example, went on-line in June near Boulder City, Nevada, covering a 350-acre site with 760 parabolic concentrators. The 64-MW plant, built and owned by Solargenix Energy, a subsidiary of Spain's Acciona Group, will sell electricity to Nevada Power Company and Sierra Pacific Power Company under a 20-year power purchase agreement. Among the technological improvements that have been developed since SEGS and incorporated into Nevada Solar One, better insulation will limit the plant's reliance on natural gas to only 2% of its backup power. Other major parabolic trough generating plants are expected to begin operation over the next two years, including installations in Spain, Morocco, Algeria, Egypt, and Mexico.

Another STE technology that was successfully demonstrated more than a decade ago has also recently been revived. Central receiver systems, or solar towers, use a field array of heliostats—large, flat mirrors that track the sun—to focus light onto a central receiver on top of a tower in the center of the array. In 1992, EPRI worked with the Department of Energy (DOE) and a group of utilities to demonstrate the use of molten salt as a heat transfer fluid and energy storage medium in a 10-MW power tower in southern California. Lessons learned from this project are now being applied to the development of similar systems elsewhere in the world.

A major advantage of both trough and central receiver systems is that their energy storage capabilities make them the most flexible of solar technologies. Current storage times of up to 18 hours enable such power plants to be dispatchable with load factors of 65–75%. Spain is currently the leader in solar tower development, with an 11-MW plant near Seville now being brought on-line in stages and two other projects planned for the near future. Meanwhile, Pacific Gas and Electric Company has signed a memorandum of understanding with Bright Source Energy to purchase at least 500 MW of power, beginning in 2010, from a series of power tower projects to be built in California.

To help support further development of these and other STE concepts, EPRI has formed the international Solar Thermal Electric Project (STEP), currently in collaboration with Electricité de France, Salt River Project, Energias de Portugal, and Public Service Company of New Mexico. STEP will model the cost and performance of various solar-thermal technologies, design novel applications, compare similar plant designs, and critically analyze vendor claims. The ultimate goal is to provide utilities with improved information and analytical tools, including engineering and economic models, for evaluating available STE applications, as well as to offer participants an opportunity to define and collaborate on demonstrations of new technologies. EPRI is also working on STE programs with DOE and the National Renewable Energy Laboratory and with global cooperative programs, such as the International Energy Agency's SolarPACES organization, to coordinate technology development activities and minimize redundancy.

Silicon photovoltaic systems engineered for low maintenance and long-term environmental exposure are being used increasingly on commercial buildings worldwide. This 457-kW array was installed on the roof of the Lufthansa terminal at Munich Airport in 2002. (photo: BP p.l.c.)

Thin-film photovoltaic cells, manufactured by depositing semiconducting materials on an inexpensive substrate, can be integrated with conventional building materials such as roofing tiles. In this 85-kW installation, CIS PV cells form an entire side of a business center in Wales. (photo: Shell Photographic Services, Shell International Ltd.)

Photovoltaics: Breakthroughs Worthy of the Name

More than a century passed between discovery of the photovoltaic (PV) effect and its first practical application in a power-producing solar array—on the Russian Sputnik 3 satellite in 1958. For years afterward, PV arrays remained so expensive that their use was restricted to such highly specialized applications. Since the 1970s, however, the price of photovoltaics has declined dramatically as efficiencies have improved and production volume has increased. By the late 1990s, installed capacity of grid-connected applications worldwide exceeded that of remote, off-grid installations, fundamentally changing the view of PV as a niche market. The first gigawatt of cumulative installed capacity was reached in 1999; total installed capacity now exceeds 5 GW.

The price of electricity produced by PV still needs to fall substantially before the technology can achieve widespread adoption as a conventional means of generation without subsidies. DOE estimates that the cost per installed watt of PV capacity must be reduced significantly to compete with fossil and nuclear generation. To meet this challenge, DOE has established a goal of reducing the average installed cost of all grid-tied PV systems to \$3.30/W in 2015, from a median value of \$6.25/W in 2000. The result, according to DOE, would be a reduction in the average wholesale cost of electricity generated by PV systems from the current 25¢/kWh to 9¢/kWh without subsidies.

For point-of-use generation, however, the economic competitiveness of PV systems is considerably different. As with any point-of-use generation technology, rooftop PV avoids the delivery cost and therefore can compete at a higher levelized cost of electricity. If substantial installation incentives are offered, as is the case in many states, a rooftop system in a residential or small commercial application may be able to compete at a cost of electricity 50% higher than would be acceptable for a central station generator. Because of this difference, some customers in favorable locations are already investing in PV rooftop systems to lower their utility bills.

Although part of the anticipated cost reduction in PV systems would probably occur anyway because of evolutionary improvements and increasing production volume, a far sharper drop in cost may result from fundamental breakthroughs in the underlying technologies. Such breakthroughs, based on use of new materials and nanotechnologies, represent the third generation of PV development.

About 95% of all PV installations still use first-generation technology—cells made from crystalline silicon, which are relatively efficient but very expensive. Usually a single crystal is drawn from a pool of molten silicon, or polycrystalline silicon is formed by cooling the molten material. In either case, the resulting block must be cut into wafers to produce cells, a process that is time-consuming and wastes a significant amount of the expensive material. Some manufacturers skip the sawing step by pulling ribbons of silicon from the melt or by solidifying thin layers on a ceramic substrate, but so far these alternatives have not resulted in significant cost savings. Individual PV cells made from crystalline silicon can achieve efficiencies of 20–25% in a laboratory setting, but commercial modules typically have efficiencies of 13–16%. If sunlight is concentrated on such cells, efficiency can be more than doubled, but the market for concentrating photovoltaics (known as CPV) is still emerging, mostly in large-scale applications.

Second-generation, thin-film PV cells are formed by depositing silicon or other semiconducting materials in layers less than 1% as thick as those in traditional solar cells onto an inexpensive substrate used to provide structural support. So far, record thin-film cell efficiencies have run in the 16–19% range, and module efficiencies of around 13% have been achieved. Commercial production, barely a decade old, is growing rapidly as potential cost savings are realized. Further improvements in thin-film technology are ultimately expected to enable it to replace crystalline silicon as the workhorse of the PV industry, particularly as the cells are integrated with conventional building materials, such as roofing tile.

Over the long term, however, technological breakthroughs based on the use of new materials and nanotechnology are expected to create a third generation of PV modules with efficiencies much higher than those typically achievable today—increasing from about 15% to more than 50%. Specifically, third-generation solar cells would substantially reduce one or more of the generic energy losses that affect both crystalline silicon and thin-film devices today. For example, creating multiple layers of cells would enable each to absorb a different part of the solar spectrum. Alternatively, optical frequencies could be shifted inside a cell to transform the solar spectrum in ways that increase absorption. The use of nanometer-sized "quantum dots" has been shown to produce more electrons for each photon of sunlight than bulk materials, and the energy of each electron might also be collected more efficiently. In addition, progress has been made in constructing carbon nanostructures that could potentially lead to new kinds of highly efficient PV cells.

In February of 2007, EPRI responded to growing utility interest in both central and distributed solar power by creating the Solar Electric Interest Group (SEIG). Two recently published reports are available that provide an update on the status of PV technology (EPRI Report 1010412) and examine the feasibility of achieving high-efficiency PV breakthroughs (EPRI Report 1012872). A major conclusion stated in both reports is that it is technically possible that PV resources will contribute about 10% of new U.S. capacity within 25 years. This conclusion is based on the assumption that at least one of the third-generation concepts just described will achieve commercialization in the coming decades, producing a three- to five-fold increase in module efficiency and a dramatic increase in economic competitiveness. To help accelerate the development process, EPRI has joined with Electricité de France in a joint research program that looks at three of the most promising new high-efficiency PV cell concepts.

Ocean Power: Harnessing Tides and Waves

Energy derived from the motion of ocean tides or waves has several potential advantages over other renewable resources, including higher power density, greater predictability, and closer proximity to major load centers. EPRI has established two collaborative programs to demonstrate ocean energy conversion in North America, involving 17 electric utilities, 2 federal agencies, several U.S. state and Canadian provincial agencies, and more than 30 technology developers. Already several participants have announced plans to build ocean energy demonstration plants, and approximately 40 preliminary permit applications have been filed with FERC, following publication of EPRI feasibility studies.

Tidal In-Stream Energy Conversion (TISEC) is leading the way, largely because the underlying technology is very similar to that of wind turbines, but with devices driven by moving water instead of moving air. As a result, TISEC turbines can benefit from decades of experience in refining and scaling up wind energy machines, including the use of advanced composite materials, power electronics, and underwater construction techniques used in offshore wind installations. In addition, because tides can be predicted years into the future, TISEC generators can sell electricity as firm power to the electricity grid, thus reducing the need for costly reserve power.

In 2005–2006, EPRI performed TISEC feasibility definition studies for seven promising locations in North America, using designs for both demonstration- and commercial-scale plants. A major conclusion of these studies was that, depending on location, plant size, and various financial assumptions, the wholesale cost of electricity for a TISEC generator at these sites would be in the range of roughly 5–12¢/kWh, making it competitive at the lower end with wind and well below the cost of trough solar-thermal technology. The studies also showed that the capacity factors of TISEC plants would be somewhat higher on the East Coast than on the West Coast because of lower diurnal inequalities—i.e., the difference between succeeding strong and weak tides.

Turbine designs of several very different types are currently being considered for TISEC application. An open-rotor turbine on a horizontal axis with 5.5-meter-diameter blades, for example, forms the basis of the Roosevelt Island Tidal Energy Project in New York City's East River. The first two of six turbines were installed in December 2006, and the 18-month experimental project will focus particularly on fish-turbine interactions and other potential environmental concerns. In contrast, the tidal project at Race Rocks in British Columbia uses a rotor assembly with an open center and no driveshaft or gearbox, mounted inside a duct that accelerates the water flow. This turbine was deployed in

Tidal In-Stream Energy Conversion (TISEC) has been studied favorably for application at seven promising sites in North America. Verdant Power's Free-Flow turbine is shown being transported for installation in New York's East River in late 2006. (photo: Kris Unger/Verdant Power, Inc.)

The Pelamis wave energy converter is a string of floating cylinders linked by hinged joints. The wave-induced motion of these joints pumps high-pressure oil through hydraulic motors that drive electric generators to produce power. (photo: Ocean Power Delivery Ltd.)

September 2006 and is expected to be fully operational by mid-2007. Other designs, including a turbine with helical blades, are also undergoing preliminary tests, but it's still too early to tell which technologies will eventually be the most successful.

Wave energy conversion lags somewhat behind TISEC, largely because the technology has no synergistic technological base, such as wind turbines, to draw on. Rather, a variety of designs are competing for initial attention, including heaving buoys that pump water to a generator, oscillating water columns in fixed structures that compress air for a turbine, and a snake-like series of floating cylinders whose movement generates electricity by means of hydraulic motors in the joints. A 2004 EPRI feasibility study showed that the potential wave energy resource in North America is considerably larger than the tidal resource. The study concluded that the cost of electricity from wave energy at a commercial scale in promising locations would now be in the range of 11–13¢/kWh, but that the cost could be expected to fall as more experience is gained. The main technical challenge is expected to be maintaining a high level of equipment reliability and plant availability for long-term energy production in a difficult environment.

Currently there are only a few megawatts of wave energy capacity deployed worldwide, and the first commercial, 30-MW plant is being installed in Portugal. The only wave project in the United States is a 40-kW buoy at the Kaneohe Marine Base in Hawaii. The first full license application for a domestic commercial wave energy plant was filed with FERC in November 2006, for a 1-MW installation at Makah Bay, Washington. Several preliminary permit applications have also been filed for other Pacific Coast locations.

Meanwhile, another key barrier to large-scale commercial development of ocean energy in the United States is regulatory. At present, both types of ocean energy conversion systems would have to go through the same licensing process that was designed more than half a century ago for conventional hydroelectric plants—although TISEC and wave energy conversion do not require any dam or water impoundment. FERC is waiving the license requirement for relatively small experimental ocean energy plants, but commercial projects are not able to move ahead as rapidly as those in other countries.

Biomass: Improving Power Options

Biomass fuel is the oldest renewable energy resource, going back to cave dwellers and their log fires. Literally before there was home, there was hearth. Even today, biomass represents the single largest source of electricity from non-hydro renewable resources, fueling more than 9700 MW of generating capacity. Most of this biomass comes from forest product and agricultural residues, with the raw material fired directly in a power plant boiler—either by itself or as a supplement to fossil fuels, particularly coal. The use of municipal solid waste for power generation is also growing.

In addition, biomass provides the only renewable alternative for producing liquid transportation fuels, a prospect that has become the focus of much government-funded research. Indeed, the current Bush administration has established a goal of replacing 30% of gasoline used in the United States with biofuels by 2030. So far, most of the liquid biofuel for U.S. transportation has been in the form of ethanol, produced by conventional fermentation of plant sugars from crops such as corn. Since redirecting this much agricultural output places pressure on the supplies of crops—particularly corn—available for food, considerable research is now devoted to finding better ways of producing ethanol from other plant materials. The cellulose fibers that hold plants erect, for example, could provide a much more abundant source of ethanol, but the conversion process is still quite expensive.

While the ethanol biofuel issue has captured most of the headlines, the electric power industry has focused largely on finding ways to use biomass directly for power generation; these options include the cofiring of biomass in fossil fuel boilers, biomass gasification as a very-low-emission alternative, direct biomass firing, and combusting biogas from landfills and anaerobic digesters. Additionally, utilities have interest in bio-based combined-heat-and-power opportunities, assessments of local

Wood chip residues from Vermont forests and sawmills supply the bulk of the fuel for Burlington Electric Department's 50-MW McNeil generating station. Biomass can be fired directly, as at McNeil, or gasified before combustion for very low emissions. (photo courtesy National Renewable Energy Laboratory) resources, and characterizations of unusual biomass supplies. To aid in these efforts, EPRI has formed the Biomass Interest Group (BIG), which provides participants with technology assessments on key development issues for materials handling, biomass delivery, and environmental performance. It is anticipated that government funding of biomass-to-power research will remain at a very low level and that EPRI will therefore continue its leadership role in communicating and demonstrating technology advances in this area.

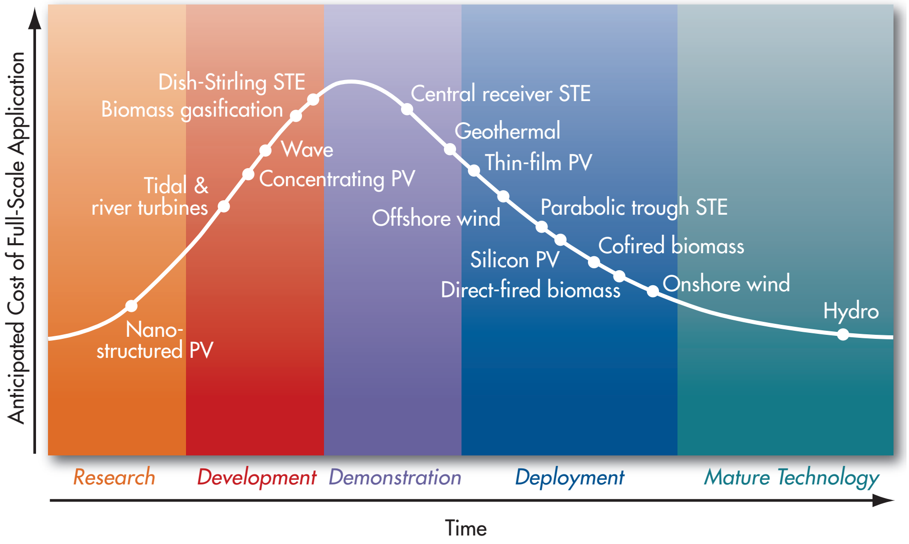
Additional research is especially needed in the near term to help biomass gain market share in power generation and in the long term to develop new biomass technologies with very low emissions. In particular, the current fleet of coal-fired plants could be evaluated for the potential to make use of biomass to cofire active units and to repower units slated for retirement in order to provide early reductions of net emissions. Longer-term reductions could result from increased public-private R&D collaboration on biomass gasification aimed at achieving higher performance and lower cost.

Supporting “Green” Energy

Renewable energy technologies are playing an increasingly important role in the effort to limit global climate change by shifting to low- and non-emitting energy resources, particularly as concerns also rise over finding ways to reduce U.S. dependence on imported petroleum. Some two dozen states now have renewable energy requirements, and consumer interest in the use of clean and diversified energy resources is clearly growing. Meanwhile, utilities are faced with increasingly complex technical issues related to integration of more renewable energy into their power systems. EPRI is responding to these trends and needs by investing in further technological development in areas of particular interest to the industry and by providing strategic information to its members on emerging technologies. In the past, EPRI has made major contributions to renewable energy technology, including the development of power electronics for variable-speed wind turbines, high-efficiency cells for CPV in central plant applications, and fish-friendly turbines for hydroelectric facilities. Now, as renewable energy technologies are being developed and deployed on a large scale throughout the world, EPRI is focusing on how to address more-specific issues involved in utility adoption of these technologies.

“EPRI is uniquely situated to help its members assess the performance of renewable generation systems and resolve problems not being effectively addressed by vendors,” says Tom Key, technical lead for renewable and hydropower generation. “In particular, we offer members vital performance and cost data in our *Renewable Energy Technical Assessment Guide*, opportunities to join renewable interest group activities, and regular updates on the status of technological developments around the world. The Institute will also continue its support of collaborative research in carefully selected areas of concern to our members.”

Renewables Technology Development



While the actual numbers vary, the cost of bringing new power options to the marketplace follows a similar trajectory for most technologies—increasing during research and development and falling off substantially after successful full-scale demonstration and as a large number of units are deployed. Investment values on the curve are positioned relative to each technology’s anticipated final RD&D cost and should not be used to compare investments among different technologies.

This article was written by John Douglas, science and technology writer. Background information was provided by Tom Key (tkey@epri.com), Terry Peterson (tpeterso@epri.com), Roger Bedard Jr. (rbedard@epri.com), Dave O’Connor (doconnor@epri.com), and Charles McGowin (cmcgowin@epri.com).

Further Reading

Solar-Thermal Electric Technology: 2006. EPRI. March 2007. Report 1012731.

Role of Renewable Energy in Sustainable Electricity Generation Portfolios: Preliminary Results and Next Steps. EPRI. January 2007. Report 1012730.

California Regional Wind Energy Forecasting System Development, Vol. 1: Executive Summary. EPRI and California Energy Commission. 2006. Report 1013262.

Solar Photovoltaic Technology Update—2005. EPRI. March 2006. Report 1010412.

Feasibility of High-Efficiency Photovoltaics Breakthrough Research. EPRI and California Energy Commission. October 2005. Report 1012872.

Nuclear

In pursuit of a Renaissance

The Story in Brief

Virtually every credible plan for dealing with climate change includes increases in the use of nuclear power—the only non-emitting technology currently capable of producing electricity at multi-gigawatt scale. Advanced reactor designs are available to support such a resurgence, but getting new plants built will require substantial work on technical, regulatory, and business issues, as well as renewal of a diminished nuclear manufacturing and construction infrastructure.

Rising and volatile fossil fuel prices and growing concern about greenhouse gas emissions are driving a "nuclear renaissance" around the world. Plant construction activities are proceeding in 12 countries, and development plans in the United States are closer to commercialization than they've been in almost 30 years. A recent report by the Intergovernmental Panel on Climate Change cites nuclear power as one of the key mitigation technologies for dealing with greenhouse gas emissions on a global scale.

EPRI, too, has looked closely at climate change mitigation options. At the request of its board of directors, EPRI examined the technical potential for reducing carbon dioxide (CO_2) emissions in the U.S. electricity sector. EPRI found that no one technology would be a so-called silver bullet. But within the portfolio of technologies needed to significantly reduce climate impacts, nuclear energy loomed large. According to EPRI's analysis, significant nuclear expansion—64 gigawatts of new capacity by 2030—could avoid approximately 260 million metric tons of CO_2 emissions annually from the U.S. electricity sector. Additional nuclear power penetration worldwide, estimated by some to be five to ten times as many gigawatts, would produce commensurately larger reductions.

The impetus to limit CO_2 emissions is increasing around the world. While the Kyoto Protocol has not been successful in uniting all nations under a common framework for addressing climate change, it has sustained international pressure to reduce greenhouse gas emissions. The European Union has been a leading force in the climate change debate, implementing a multinational trading scheme for CO_2 emissions. China, which recently surpassed the United States as the world's largest CO_2 emitter, has also increased its awareness of and participation in international climate change discussions. Nuclear power is growing in China, and the country has stated it wants 16% of its electricity to come from renewables by 2020.

Pressure to limit CO_2 emissions is mounting in the United States as well. Some states and regions are already imposing limits on such emissions, and numerous corporations, institutions, and financial groups are pressing Congress to pass emission-control legislation. Clearly, expected legislative action on CO_2 and other greenhouse gases has helped promote interest in non-emitting energy sources, such as renewable energy and nuclear power. But in practical terms, what impact might such limits have on the decision to build a new nuclear plant? The question is complicated by uncertainty over what regulatory approach might be adopted—a carbon tax or an emissions cap-and-trade system, for example—and about how such a system would be administered.

Still, the seeming inevitability of federal legislation has electric utilities taking a fresh look at the impacts of carbon constraints on the cost-competitiveness of new plants. "In our financial modeling, we've looked at something as small as a \$10-per-ton tax, and it has an enormous impact when we do the least-cost supply option forecast," says Randy Hutchinson, Entergy Nuclear's senior vice president, nuclear business development and new plant activities. "Nuclear power plants become much more competitive with other baseload options such as coal when a tax is included in the analysis."

Recent EPRI economic modeling of the U.S. electricity sector's potential to reduce greenhouse emissions compares different technology scenarios—including limited versus significant construction of new nuclear and advanced clean coal plants—out to 2050. Initial results emerging from this analysis indicate that costs to the U.S. economy of CO_2 emissions abatement are dramatically lower in scenarios where a full array of advanced technologies are developed, available, and aggressively deployed. A substantially expanded nuclear power fleet plays a large role in such scenarios.

Running such economic scenarios will be important for a company's commitment to new plants, but as Eugene Grecheck, vice president for nuclear support services at Dominion, points out, many company boards are looking beyond the details of coming mandatory carbon limits: "Boards tend to look further into the future, and won't wait for a mandatory cap. They realize that we need to start planning now for how to address carbon controls of some type." Bryan Dolan, Duke Energy's vice president for nuclear plant development, expresses a similar bottom-line view, held by many in the industry: "Anything imposing additional carbon constraints on the legislative front may sway decision-making more toward nuclear."

Nuclear's status as a CO_2 non-emitter is also changing minds among some longtime opponents of the technology. Patrick Moore, a cofounder of Greenpeace, told the U.S. House Appropriations Subcommittee on Energy and Water Development at a September 2006 hearing that in the 1970s he believed "nuclear energy was synonymous with nuclear holocaust." But a lot has changed in the 35 years since then, he said. "Nuclear energy is the only large-scale, cost-effective energy source that can reduce CO_2 emissions while continuing to satisfy a growing demand for power—cleanly and safely."

The environmental community is far from united in supporting a nuclear renaissance, but the change of position from activists such as Moore reflects a broader rethinking of the nuclear option among opinion leaders and the public at large. Over the past five years, opinion polls have consistently shown increasing public acceptance of the technology, encouraged by major coverage in virtually all the national newspapers and newsmagazines on the "greening of nuclear power."

Building on Success

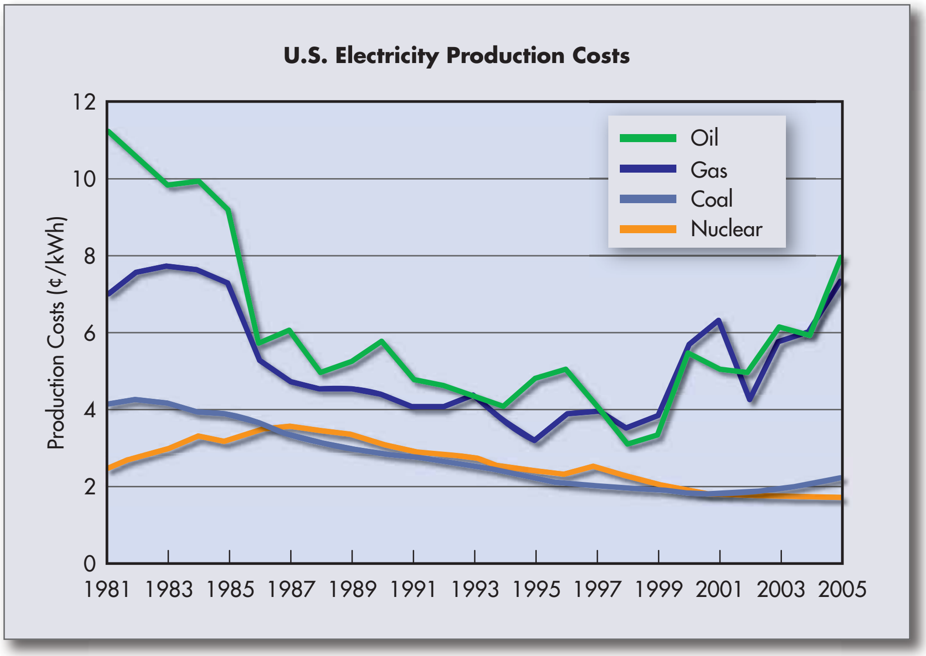
While the ability to generate emission-free electricity will certainly help promote public acceptance, renewed interest in new nuclear plants is just as grounded in the fundamentals of the power business, says Tom Mulford, manager of EPRI's Advanced Nuclear Technology Program. "The current U.S. nuclear fleet is extremely safe and reliable, and it's currently operating at a capacity factor of more than 90%. A number of financial analysts have concurred that the nuclear resurgence is tied largely to the sustained high performance of the existing reactor fleet."

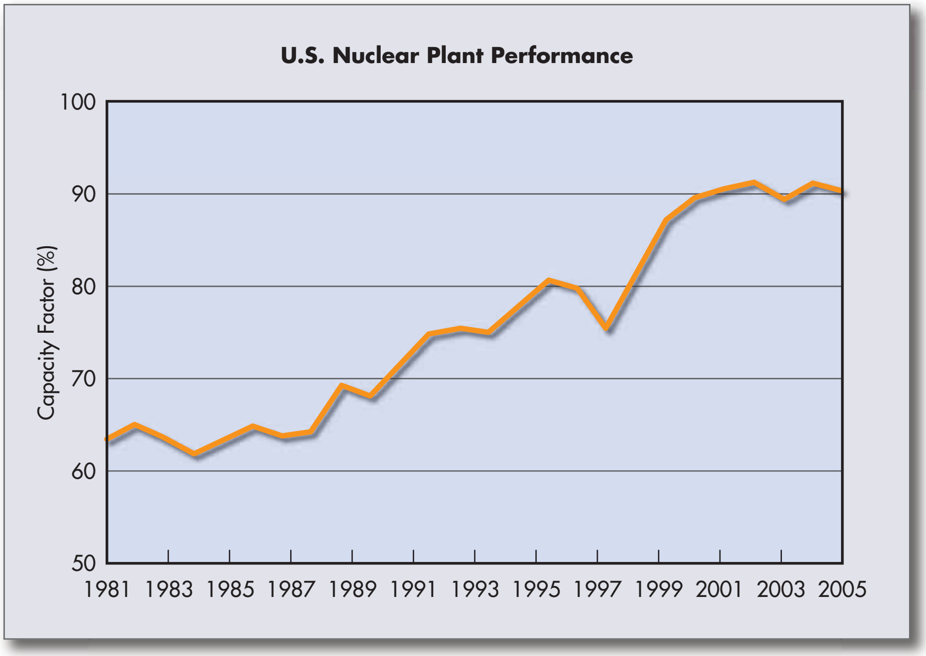
Attention to nuclear safety remains paramount among plant staff as well as the public. Analysis by EPRI—and measurements of specific safety metrics set by the industry and the Nuclear Regulatory Commission (NRC)—confirm the ever-improving safety record of the U.S. nuclear fleet. In addition, EPRI research suggests a link between reliability and safety, indicating that the nuclear fleet is operating not only at high capacity, but with an unprecedented level of safety.

Mulford also points out that nuclear energy is one of the lowest-cost energy sources available today, particularly for baseload power. In the United States, for example, electricity production costs in 2005 for nuclear power were 1.72¢/kWh, according to the Nuclear Energy Institute (NEI), compared with 2.21¢/kWh for coal and 7.51¢/kWh for natural gas. Moreover, nuclear fuel costs are not volatile and account for only a small portion of overall production costs, thus providing excellent overall price stability. Andy White, president and CEO of GE-Hitachi Nuclear Energy, puts it this way: "A 50% increase in fuel costs for a natural-gas-fired plant raises operating costs by about 38%. For a coal-fired plant, operating costs go up by about 20%. For a nuclear plant, a 50% increase in fuel costs increases operating costs by only 3%."

Reliability and efficiency improvements have enabled nuclear plants to boost electricity production at individual sites, and ongoing operational advances could increase output even further. Electricity demand will grow much faster than gains in nuclear plant efficiency, however. The Department of Energy's Energy Information Administration (EIA) projects world electricity demand to increase 85% by 2030, with the strongest growth in emerging economies. In the United States, the EIA expects electricity demand to surge by 45% over the next 25 years. This increase translates into a need for nearly 350,000 MW of new electric generating capacity, much of it baseload—coal-fired and nuclear power plants. About 60,000 MW of new generating capacity will be required in the next 10 years alone, according to the EIA.

Considering this need and the capabilities of today's technologies, it's clear that new nuclear capacity must provide a substantial portion of the coming decades' generation mix. "We're not saying that nuclear energy is the only answer," says Domin-





Renewed interest in nuclear power has been supported by a quarter century of low costs and substantially improved reliability for the existing nuclear fleet. The NRC confirms that safety records have also improved steadily over this period. (source: NEI) ion's Grecheck. "Solar, wind, and other renewables have a role to play, but they're not currently practical on a large scale."

Cost and Risk

Most nuclear utilities and vendors identify the same challenges to building new nuclear plants, and not surprisingly, the overriding issues come down to cost and investment risk. Given the U.S. industry's experience in the 1970s and 1980s, when licensing and construction delays led to escalating costs, building new nuclear plants is a tremendous risk management exercise, notes Richard Myers, vice president of policy development at NEI. "Numerous nuclear utilities are preparing license applications for new plants, but no company will make a commitment to build a new plant unless it has a high level of confidence in the cost and schedule. We are trying to identify all the project risks and make sure they're mitigated and managed and properly hedged," he says.

One key challenge is the need to confirm competitive capital costs for new nuclear plants. "Vendors need to provide firm costs to their customers," says Buzz Miller, senior vice president for nuclear development at Southern Nuclear. "Most new plants will be built in regulated states in the southeastern United States. We need pricing at a level of certainty that will be acceptable to our public utility commissions." Southern is preparing a license application for two new AP1000 units at the Plant Vogtle site, and it needs to convince the Georgia Public Service Commission (PSC) that these units will be cost-competitive with other generating sources, including coal and natural gas. Southern is working with Westinghouse, the AP1000 vendor, and expects to have the figures it needs to support a submittal to the PSC in mid-2008, which would result in PSC certification around December 2008. Vendors recognize that most of their customers are regulated, says Ed Cummins, vice president of licensing and standardization for Westinghouse. "We are trying to provide a degree of firmness in price that would permit them to interact with their public utility regulators."

Similarly, Dominion is working with GE Energy on pricing for the Economic Simplified Boiling Water Reactor (ESBWR), while Constellation expects to have 70–75% of Areva Inc.'s U.S. Evolutionary Power Reactor (EPR) at a fixed price, excluding labor, by late 2009 and early 2010. TXU, which has selected Mitsubishi's U.S. Advanced Pressurized Water Reactor, expects production costs based on the US-APWR to be competitive in Texas's deregulated market within the next year or two.

GE Energy's White admits that the company is working with estimates at present, but he expects to have "locked down the engineering-procurement-construction (EPC) contracts" by the end of 2008. "One question is where commodity prices will be during a 2010–2015 construction timeframe," he says. Areva is closer to pricing certainty than it was a year ago, says Ronald Affolter, vice president for EPR deployment. Ongoing construction of an EPR plant in Finland has helped the company better understand the potential costs of a U.S. plant.

Advanced modeling tools can provide insight into nuclear project costs. In a program sponsored by EPRI, Westinghouse developed a virtual reality construction model of the AP1000 reactor design to assess the impact of two drivers of plant construction costs—the cost of financing during construction and the substantial skilled craft labor needed on-site during construction. The virtual reality model identified opportunities for reducing both cost drivers by establishing parallel construction paths using modules and integrating construction sequence review into the design process. According to EPRI, the model should reduce construction times for advanced reactors by 10%.

Standardization

Many of the risk factors that nuclear companies must deal with are beyond their control. One issue that is clearly within the industry's control is standardization: standardization of design requirements, standardization of resulting advanced designs, and standardization of operations. The industry has devoted significant time and resources to this issue over the past few decades. In the 1980s and 1990s, EPRI led efforts to create a standardization framework that would guide new plant development and deployment. The Utility Requirements Document (URD) captured user requirements for advanced reactor designs that utilities reached consensus on and that the reactor designers and the NRC could accept. The nuclear industry's *Strategic Plan to Build New Nuclear Power Plants,* an annual report updated each year through the 1990s, laid the foundation for efforts of both reactor vendors and utility consortia to maintain cost-effective standardization in new plant projects under development today.

The URD is a living document, with periodic revisions to reflect technology advances and lessons learned from operating plants. EPRI, through its technology transfer capabilities, is sharing information from R&D activities in a number of areas, including radioactive waste, materials, water chemistry, systems engineering and design, human factors engineering, instrumentation and control, electrical cabling, equipment qualification, and seismic design. Updates in these areas are being shared continually with utilities and vendors and will be documented in a subsequent URD revision.

Standardization implies industrywide resolution of common issues. "The utilities that are expected to submit combined construction and operating license applications to the NRC are basing their applications on several different reactor designs," says EPRI's Mulford. "While these reactors have a host of specific design differences, there remain a number of issues that are generic to more than one design, such as seismic issues and digital instrumentation and control. Addressing these issues in a collaborative fashion ensures continuity with the URD and enables lessons learned

Snapshot of Advanced Reactors

Unlike today's nuclear plants, the reactors proposed for new plants have standardized designs with innovative safety features. Two reactors being considered for construction—the Westinghouse AP1000 and General Electric's Economic Simplified Boiling Water Reactor (ESBWR)—are advanced, "passive safety" designs that rely on natural forces such as gravity for plant safety, rather than on pumps or fans. Both employ a modular design. Three other reactors under consideration—Areva's Evolutionary Power Reactor (EPR), General Electric's Advanced Boiling Water Reactor (ABWR), and Mitsubishi's U.S. Advanced Pressurized Water Reactor (US-APWR)—are evolutionary designs. Although based on current plants, these reactors have enhanced safety features.

The Westinghouse AP1000, a 1000-MW pressurized water reactor (PWR), has significantly fewer components than today's PWRs. It has 50% fewer valves, 35% fewer pumps, 83% less pipework, and 87% less control cable. In addition, the design reduces by 45% the amount of building materials required. The reactor's safety system uses gravity, natural circulation, and compressed gas to ensure emergency core cooling and employs no pumps, fans, diesels, chillers, or other rotating machines in safety applications that could malfunction or lose power in an emergency.

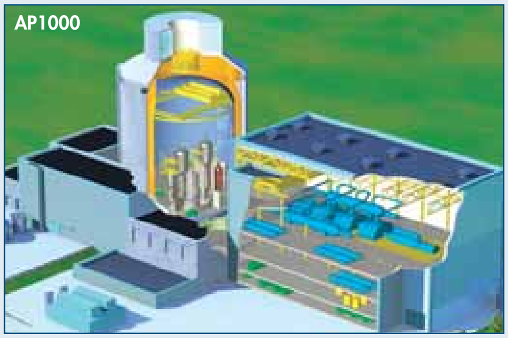
General Electric's ESBWR, a 1500-MW boiling water reactor (BWR), has reduced the number of systems by 25% and contains 25% fewer pumps and valves and 25% less piping and cabling than conventional designs. Its natural circulation and passive safety features eliminate the need for safety system pumps and safety diesel generators. For example, the ESBWR has a gravity-driven cooling system for the reactor and a passive containment cooling system that removes heat by means of four low-pressure natural circulation loops, each with a heat exchanger.

Areva's EPR, an evolutionary PWR designed by Framatome ANP, incorporates simplified safety systems that improve accident prevention and protection against external hazards. It features a robust containment structure consisting of two cylindrical walls—an inner prestressed wall with a steel liner and an outer reinforced-concrete wall, each with a separate dome. The EPR being deployed in the U.S. market has been designed to use 7% less uranium fuel per kilowatthour, reducing the cost of electricity generation. The first EPR is under construction in Finland; construction of a second EPR will begin in France by the end of 2007.

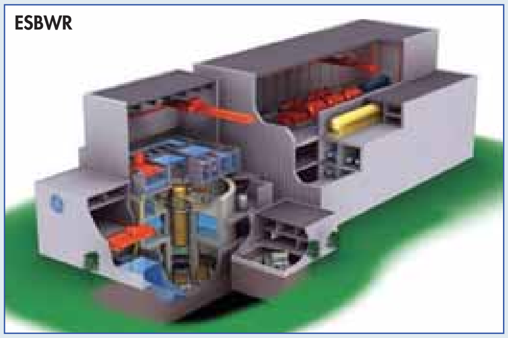
General Electric's ABWR employs a more compact design than the current BWR, increasing safety and reducing construction costs. All major equipment and components have been engineered for improved reliability and ease of maintenance—including such features as vessel-mounted reactor internal pumps and fine-motion control rod drives. This design was certified by the NRC in 1997. The first two ABWRs went into commercial operation in Japan in 1996 and 1997 at the Kashiwazaki-Kariwa site. Two ABWRs are under construction in Taiwan at the Lungmen site.

Mitsubishi's US-APWR, an evolutionary design with active safety features, is a 1700-MW reactor. Twenty-three versions of the basic Mitsubishi design are now operating in Japan.

AP1000

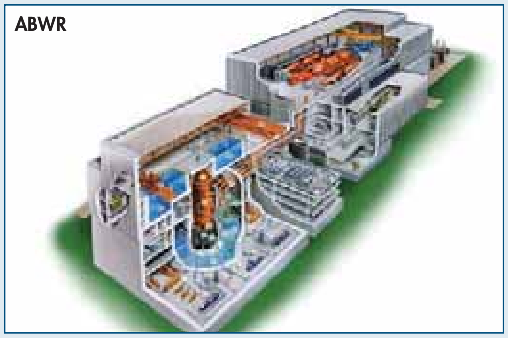


ESBWR



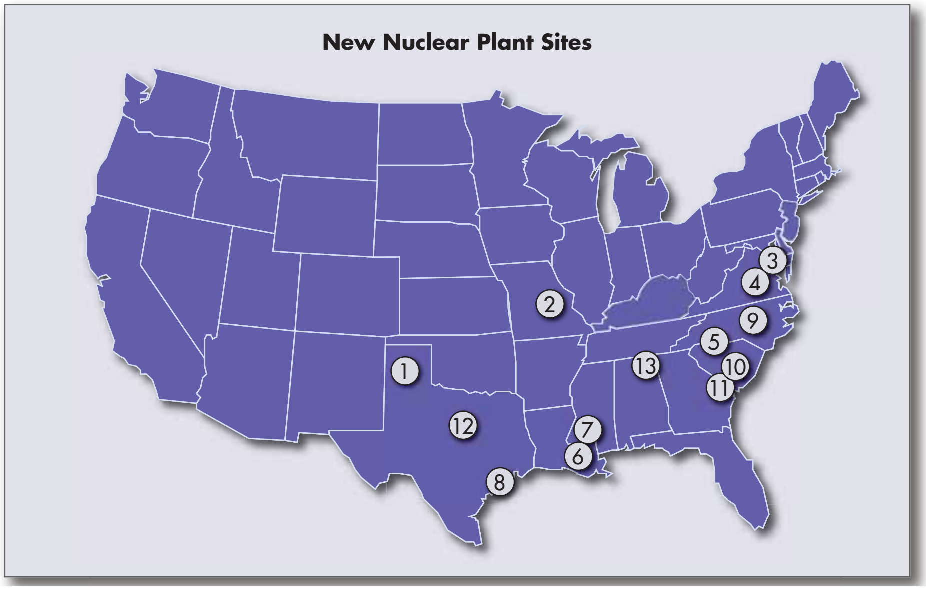
EPR

ABWR



US-APWR

A new licensing process established by the NRC in 1989 will help utilities avoid the expensive delays and redesigns that plagued nuclear plant construction in the 1970s. Applications for combined construction and operating licenses (COLs) are expected to be submitted for over a dozen new U.S. nuclear plants by the end of 2008. (source: NEI)



	Company	Site	Design	Number of Units
1	Amarillo Power	Amarillo, TX	EPR	1
2	AmerenUE	Callaway, MO	EPR	1
3	Constellation (UniStar consortium)	Calvert Cliffs, MD, plus two other sites	EPR	3
4	Dominion	North Anna, VA	ESBWR	1
5	Duke	Cherokee County, SC	AP1000	2
6	Entergy	River Bend, LA	ESBWR	1
7	Entergy (NuStart consortium)	Grand Gulf, MS	ESBWR	1
8	NRG Energy/STPNOC	Bay City, TX	ABWR	2
9	Progress Energy	Harris, NC	AP1000	2
10	South Carolina Electric & Gas	Summer, SC	AP1000	2
11	Southern Company	Vogtle, GA	AP1000	2
12	Texas Utilities	Comanche Peak, TX	US-APWR	2
13	TVA (NuStart consortium)	Bellefonte, AL	AP1000	2

from the existing fleet to be reflected in new plant designs, minimizing risks in critical areas such as materials and equipment reliability."

Financing and Loan Guarantees

As multi-billion-dollar investments, nuclear power plants present a formidable financing challenge. In a number of countries, government support, government ownership, and/or high electricity prices can make the large investment more palatable, but the hefty price tag invariably raises the level of scrutiny.

In the United States and other countries with deregulated wholesale markets, private development, ownership, and operation further accentuate the investment challenge. A new nuclear plant would represent an extremely significant part of a company's total value, according to Dominion's Eugene Grecheck: "We're at the critical stage, and companies need to work on financing packages right now." Mike Wallace, president of Constellation Energy's generation group, agrees, adding: "We can't get past this barrier without loan guarantees. We haven't begun construction of a nuclear plant for 25 years, when there were more than a few financial problems; the risks of putting up a new plant with a new design in today's business environment can't be adequately described or costed out. If banks are going to underwrite the debt for such a plant, they're going to require that somebody guarantee the loan."

In the United States, the Energy Policy Act of 2005 provides several incentives for new nuclear plants, including loan guarantees. Under the legislation, the Department of Energy guarantees up to 80% of the project cost to support the development of innovative energy technologies that avoid, reduce, or sequester air pollutants or greenhouse gases. Uncertainties have recently arisen, both about congressional appropriations for the guarantees and about the DOE guidelines that define how the policy act incentives will be administered; while these issues are currently unresolved, industry experts remain confident that government-backed loan guarantees will be available for new nuclear plants.

The financial community understands the business case for new nuclear, says Caren Byrd, executive director of Morgan Stanley's Global Utility and Power Group. "We see the need for new capacity and understand how companies have been hurt by the volatility of natural gas, which has been difficult on investors. Also, more investors are environmentally sensitive and want to invest in environmentally friendly projects. But the most important factor is economics. The financial community is waiting to be convinced on that."

Plant Licensing

Most U.S. nuclear power plants were licensed during the 1960s and 1970s. Plants were issued a construction permit based

Challenges for Existing Plants

While most plans for dealing with climate change include substantial increases in new nuclear power, addressing the climate issue will also require continued operation of existing nuclear plants around the globe. Sustained contributions to CO_2 reductions are projected to call for operating lifetimes of at least 60 years for the world's nuclear fleet.

This vote of confidence is reassuring to nuclear power proponents, but it is not a guarantee that nuclear's future is secure. "To ensure safe, cost-effective operation for 60 or more years, nuclear plants must address a number of challenges associated with the plants' physical integrity and staffing," says Ken Huffman, EPRI technical director, plant technology. "In particular, plants must continue to resolve materials degradation issues, ensure sustained equipment reliability, address equipment obsolescence and supply chain issues, and provide a trained workforce to replace retiring employees and maintain plant performance at the high levels necessary for economic operation."

The industry's ability to recognize and react to emerging materials issues has been clearly demonstrated. For example, much has been learned about the performance of materials in the primary systems of existing nuclear power plants, especially in relation to BWR recirculation piping, PWR steam generator tubing, and PWR vessel head penetrations. Nevertheless, as plants enter their fourth, fifth, and sixth decades of operation, new materials-aging issues can be expected that will require rapid response. This response will depend on the availability of robust and sensitive detection technology and on a workforce attuned to subtle indications and with a detailed awareness of system and materials performance under various operating conditions.

The cross-cutting nature of these challenges—spanning technical, operational, and management concerns—calls for optimization strategies that encompass the total nuclear plant asset. Scenario-based studies performed by EPRI highlight several societal and environmental benefits that would accrue from optimization strategies at existing nuclear plants: significant economic benefits from higher plant capacity factors and extended plant life, greater CO_2 reductions compared with other proven large-scale generation sources, and provision of a bridge between the current nuclear fleet and the startup of significant nuclear "new build" plants.

"The incremental value of increased nuclear plant performance and output—in comparison with initial performance—is estimated to be on the order of two trillion dollars in the United States alone," says Huffman. Extending these benefits to plants around the world would substantially amplify the economic value while sustaining nuclear power's ability to reduce global CO_2 emissions.

on a preliminary design, but safety issues were not fully resolved until the plant was essentially complete—a process flaw that led to a "design as you go" construction process with substantial rework that had major financial implications. The other critical flaw in the old process was the fact that the public did not have access to the details of the design or an opportunity to comment until construction was almost finished. To address this problem in the United States, the NRC established a new licensing process in 1989, which was affirmed and strengthened by Congress as part of the 1992 Energy Policy Act.

The new process has three components: approval of standard reactor designs, early site permits (ESPs), and combined construction and operating licenses (COLs). The ESP enables nuclear utilities to obtain public input and NRC approval for a nuclear plant site before committing to build a plant. The use of approved, standardized designs is intended to eliminate the ad hoc redesigns and construction delays that plagued projects in the 1970s. The process also gives the public an opportunity to comment on the design before it is approved. The public is given another opportunity for comment at the COL stage, when a particular certified design is matched to a preapproved site. When the NRC grants a COL, it signifies resolution of all safety issues associated with both the site and the plant.

While these improvements are encouraging, the nuclear and financial communities are awaiting clear signs that the NRC's new process will be effective and efficient. As Morgan Stanley's Byrd points out, "On paper, the process makes sense, but it hasn't been tested."

The NRC's ability to handle the new plant licensing workload will certainly need to be demonstrated. But another key point for utilities will be the COL application itself—essentially the need to understand what review criteria and implementation measures the NRC will use in assessing COL applications. Some companies have begun preparing applications without knowing "what they need to look like," but the majority are awaiting the official release of the regulatory guide for the application contents, expected this summer.

NEI's Adrian Heymer, senior director for new plant development, says that the NRC is doing the right things to encourage an efficient process, with emphasis on standardization of submittals and reviews. In addition to encouraging all applications for a specific design to be as standardized as possible, the NRC is promoting standard processes and technical issue resolutions across different designs. The NRC also has advocated the creation of designcentered working groups among utility applicants, with corresponding NRC staff organizational teams, each responsible for reviewing all applications for a given design. "Once the NRC has reviewed and approved the reference plant submitted by the working group," Heymer says, "it is our understanding that the NRC will then check the next application for the same design and focus on site-specific differences. It should be possible to achieve significant efficiencies and improvements in the schedule after the reference plant review."

Because the end-to-end permitting and approval process is untested, disciplined navigation will be essential. Tools developed from past and current activities can guide the way. To help utilities select a suitable site for a new nuclear plant, EPRI developed a siting guide and an early site permit model program plan. The guide describes a four-step process that addresses the full range of issues important to siting, while the ESP model program plan identifies the tasks needed to prepare an ESP application. EPRI also has developed a combined construction and operating license model program plan, which identifies the activities needed to supply the information required for a COL application. The program plan describes the interfaces between the vendor, the ESP holder, the architect-engineer, and other entities involved in preparing a COL application.

Getting the Plants Built

Although modest nuclear plant construction has continued around the world for much of the past 25 years, the population of manufacturers capable of supplying nuclear equipment has diminished because of the limited number of projects. The decades-long hiatus in North American plant orders has had a withering effect on what was once a vibrant nuclear manufacturing base in the United States. As a result, the first batch of new plants is likely to face bottlenecks in availability of key components. Increased demand will eventually lead to greater manufacturing capacity, but not surprisingly, vendors see the supply chain as a major challenge.

At present, only one company in the world—Japan Steel Works (JSW)—manufactures the ultraheavy forgings needed for nuclear plants. "JSW currently has the capacity to produce about 42 ultralarge forgings a year; each new plant will require between two and nine of these forgings, depending on the design," says NEI's Heymer. According to Entergy Nuclear's Hutchinson, a reactor pressure vessel has a lead time of 48 months from the placing of the order to the shipment of the vessel. "JSW's throughput is six to eight pressure vessels a year, maximum, so for the first plant orders, this will be a pinch point." For this reason, vendors are already talking with JSW about their future needs. GE Energy has entered into a reservation agreement with JSW, securing a specific number of forging allocations for the next few years. Westinghouse and Areva are also in the JSW queue.

GE Energy's White says that JSW is planning to expand its manufacturing capacity to serve the larger expected demand, but he believes that in the longer term, multiple suppliers will enter the market. Currently, says Westinghouse's Cummins, "it's a chicken-and-egg situation. If suppliers are assured of a market, they will assess capacity and expand to meet the demand; if they are not assured, they will wait to make an investment. There will be shortages or constraints in the supply chain as we build the initial plants, but they will disappear over time. I think there will be alternatives to JSW."

Pressure vessels are not the only concern. To identify choke points, vendors are systematically looking across the entire supply chain, noting the numbers and types of components needed and looking at what is available. Components that are especially critical to reactor safety must be manufactured under a special process of rigorous quality assurance to achieve the designation "nuclear grade." As NRC Chairman Dale Klein told the House Appropriations Subcommittee on Energy and Water Development in March 2007, "The NRC is working with regulators in other countries to ensure the legitimacy and quality of components manufactured internationally."

A limited workforce of both craft workers and construction managers could lead to additional bottlenecks in new plant construction, particularly in Europe and the United States. There are shortages of skilled pipe fitters, welders, journeymen, sheet-metal workers, carpenters, and technicians. "Having seasoned project managers and experienced people to oversee the craft workers will be critical to building plants on time," says NEI's Heymer. The U.S. nuclear industry is working with several federal agencies, as well as community colleges, to ensure the availability of a skilled workforce. "We'll have to train people, and we'll have to import people," says Westinghouse's Cummins. Some utility executives see a similar shortage in their own organizations and expect at least some of the experienced project managers to come from other countries.

Labor availability concerns highlight the importance of effective training—equipping employees with the requisite knowledge and skill to successfully perform in a cross-discipline environment. As new personnel enter the nuclear workforce, training must accelerate the learning process without compromising the demonstrated proficiency levels required for nuclear workers.

The availability of skilled craft workers in the United States will not be a big issue when only two or three plants are under construction, says GE-Hitachi's White. "But if 6, 10, 12 plants are being built simultaneously, it will be difficult to get craft labor." One factor that may ease the demand for skilled craft workers is the use of modular construction. Building modules in a controlled environment—a factory or a shipyard—could raise productivity, says White. "It also could avoid sucking up all the labor supply in the area of the plant site."

Task proficiency evaluation (TPE), a

Spent Fuel Storage: A Showstopper?

In 1987, Congress directed the U.S. Department of Energy to study Yucca Mountain, Nevada—a remote desert location—as the site for a potential repository for geologic disposal of used nuclear fuel and high-level radioactive waste. DOE's study of the site was delayed until 1992, in part because of the refusal of Nevada to issue the environmental permits needed for surface-disturbing work. After a decade of scientific study, the site was approved by Congress in 2002.

Construction of the repository, originally scheduled to open in 1998, has been repeatedly delayed because of funding constraints and DOE management issues. Opposition from the Nevada congressional delegation has played a role in DOE budget cuts for the project. DOE was to begin accepting used fuel from the nation's nuclear power plants in 1998 but failed to do so. This failure led to numerous lawsuits by the industry against the federal government for breach of contracts that DOE had signed with electric utilities. DOE now plans to submit a license application to the Nuclear Regulatory Commission in 2008 to build the repository, which is not likely to open before 2021. Used nuclear fuel is now safely stored at nuclear plant sites. Although the NRC has determined that used fuel could be stored safely at plant sites for 100 years, on-site storage was never intended as anything other than a temporary solution.

Is used fuel an obstacle to new plant construction? Most nuclear utilities and vendors do not think so. "We don't see the management of used fuel as a showstopper to moving forward," says Duke Energy's Bryan Dolan. Adds Southern Nuclear's Buzz Miller, "It's not a safety issue. It's a political issue, a contractual issue." To this point, EPRI commissioned studies in 2003 and 2004 to assess the risk of moving used fuel from the fuel pool into on-site dry storage. The results indicated that the annual risk of a cancer fatality to an individual living within 100 to 300 meters of a plant's loading, on-site transfer, and dry storage operations is essentially zero.

Some in the industry do think that disposal of used fuel is an issue, says Ed Cummins from Westinghouse. He says that could affect the number of new plants built. Opponents to new nuclear plant construction often point to the legislative limit on used fuel to be stored at Yucca Mountain. A 2006 EPRI study, however, demonstrates that the technical capacity of Yucca Mountain as a repository is actually four to nine times the legislative limit. This additional capacity would enable two to four times the existing U.S. nuclear installed capacity to operate for 60 years, with all used fuel stored at Yucca Mountain.

---

workforce approach advanced by EPRI in conjunction with utilities, trade unions, and labor suppliers, defines the key knowledge and skills required to perform specific tasks. In developing the TPE program, EPRI has created a bank of written and practical skill assessment tests for many of the defined tasks given to craft personnel. To further streamline personnel use and productivity on multiple projects, the program is also working to share information on individuals who have successfully demonstrated specific task skills.

Looking Ahead

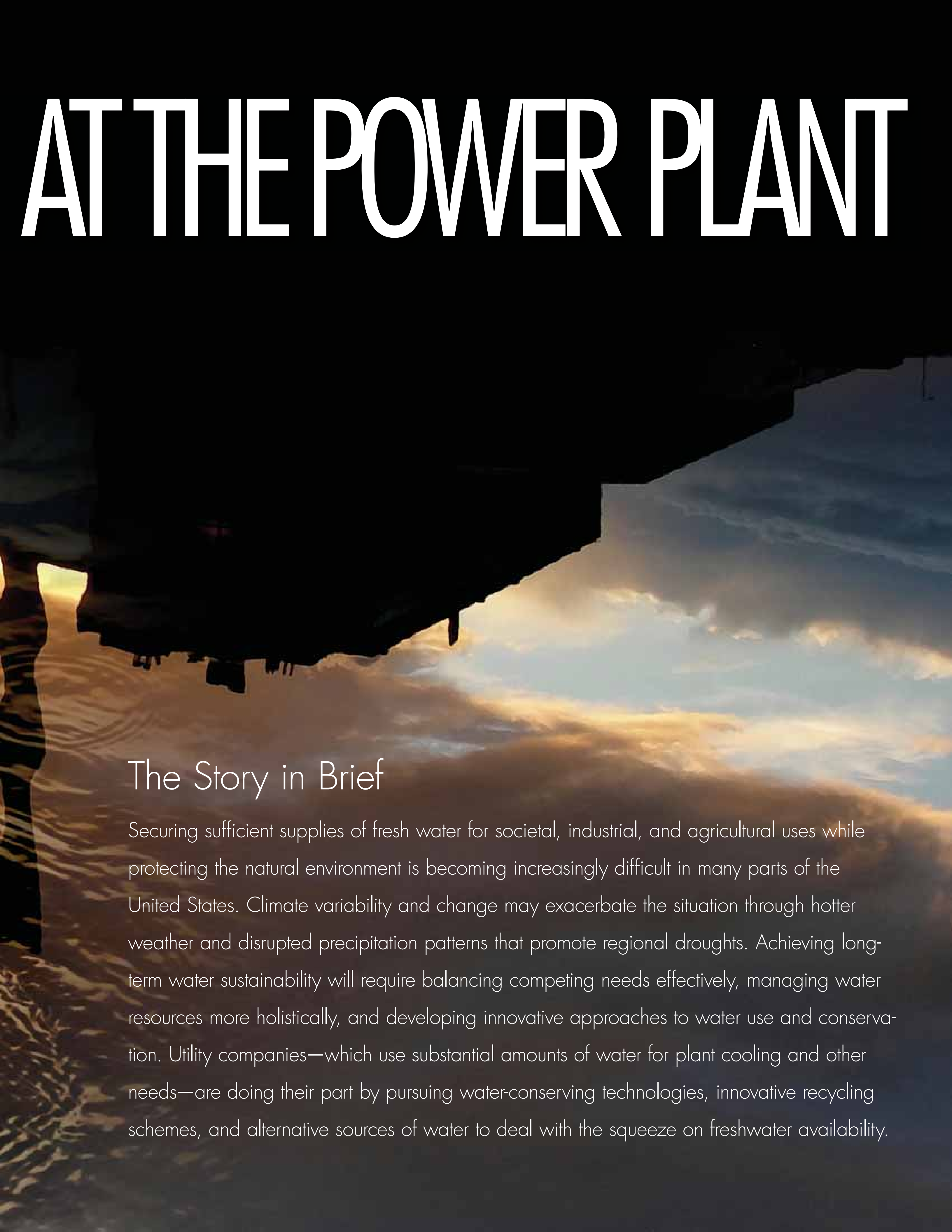
Superior plant designs, streamlined licensing approaches, and strong coordination among utilities, vendors, suppliers, industry associations, and regulators are key ingredients to a resurgent nuclear industry, regardless of where the plant is being built. The interdependent nature of nuclear plant operation creates a community in which lessons learned and collaboration continuously guide process improvements. As more nuclear plants proceed from design certification through licensing, procurement, construction, and preservice inspection and testing to operation, capitalizing on these global strengths will be paramount. Sustaining this engagement over the lives of the plants will ensure that nuclear power can remain a reliable nonemitting electricity source.

Although the nuclear industry has gained significant momentum over the past few years, the nuclear renaissance is still in its earliest stages. The full scope and success of the renaissance will be realized only over time, as operating licenses are issued in many more countries around the world, as financing is secured, as foundations are being poured, and as a new generation of nuclear power plant personnel begin delivering emission-free electricity to the grid—from Mississippi to Mumbai. Building on the opportunities embedded in the climate change issue, and appreciating the sobering responsibility associated with nuclear power generation, the industry is poised to move the renaissance from abstraction to reality.

This article was written by Alice Clamp. Background information was provided by Tom Mulford (tmulford@epri.com) and Gary Vine (gvine@epri.com).

RUNNING DRY

AT THE POWER PLANT



The Story in Brief

Securing sufficient supplies of fresh water for societal, industrial, and agricultural uses while protecting the natural environment is becoming increasingly difficult in many parts of the United States. Climate variability and change may exacerbate the situation through hotter weather and disrupted precipitation patterns that promote regional droughts. Achieving long-term water sustainability will require balancing competing needs effectively, managing water resources more holistically, and developing innovative approaches to water use and conservation. Utility companies—which use substantial amounts of water for plant cooling and other needs—are doing their part by pursuing water-conserving technologies, innovative recycling schemes, and alternative sources of water to deal with the squeeze on freshwater availability.

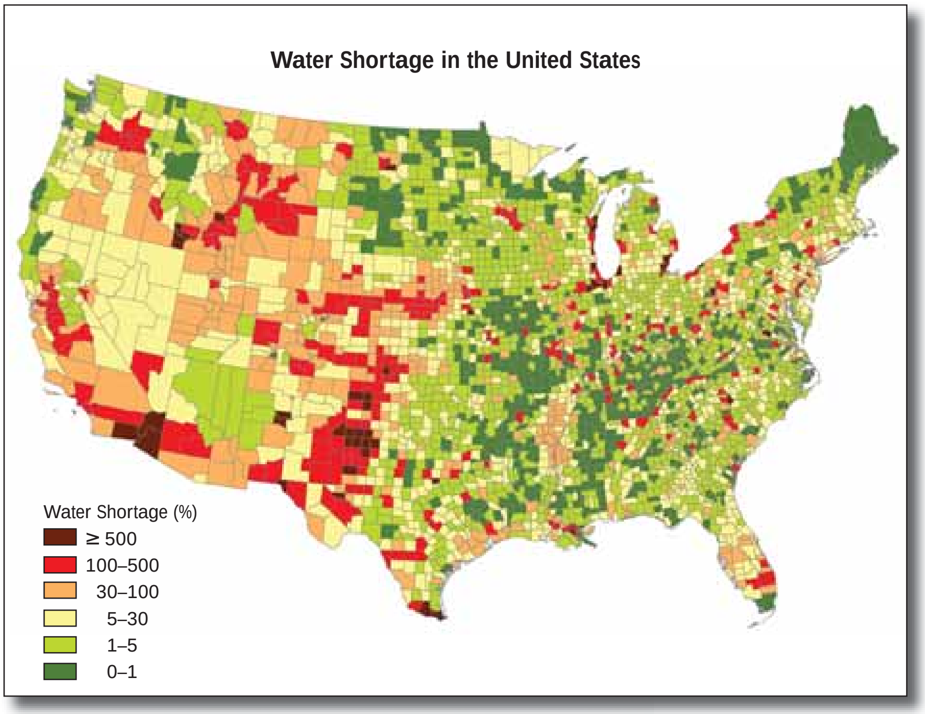
Seventy-five percent of the water used in the western United States begins as snowpack stored in the high mountains. As the days lengthen into spring and summer, the runoff feeds the region's great watersheds and rivers, where it is captured and stored a second and third time in an extensive infrastructure of dams and reservoirs. From there the water is parceled out in increasingly complex formulas to farmers and ranchers, to cities and municipalities, and to wildlife and the environment. While the supply of fresh water in the West appears to be declining, population continues to grow, bringing with it not only increasing competition for water but the search for a long-term sustainable solution.

Over the next 25 years, the United States will add 70 million people, with most of the population growth concentrated in the water-short areas of the Southwest, the Far West, and even the Southeast. Los Angeles may have been the harbinger of desert urbanization. The city was built on the presumption of fresh water: the city reasoned that if it imported water in abundance, people would follow and the desert would bloom. The strategy worked. Today, greater Los Angeles stretches out to cover nearly 5000 square miles of irrigated land. Similar scenarios are now playing out in some of the country's fastest-growing cities—Las Vegas, Phoenix, and Salt Lake—despite the prospect of long-term drought looming over the West. Snowpack levels are down throughout the mountain region, and with warmer temperatures, the spring runoff now begins 10 days earlier on average. Meanwhile, to sustain its growth trajectory, Las Vegas is trying to bring groundwater 280 miles from the northern valleys of Nevada despite opposition from local farmers and ranchers, and the booming exurbs of Salt Lake have proposed a 120-mile pipeline to tap into Lake Powell, which is now at its lowest level since 1973.

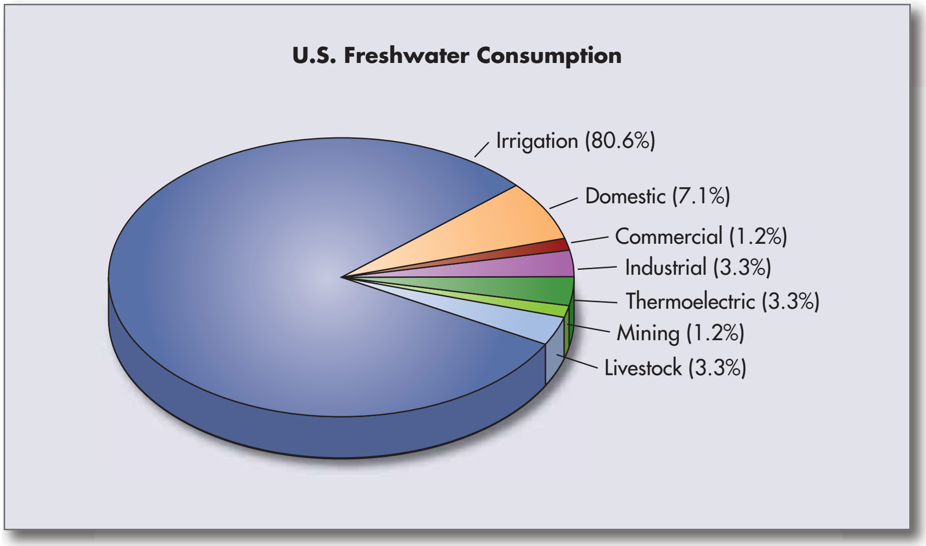
Water Sustainability

Water sustainability is not just a western concern. It is an issue throughout the United States and in most areas of the world where population pressures are mounting. According to the Government Accountability Office, 46 states expect water shortages over the next 10 years; some of the shortages will be statewide, others will be more localized. Few new reservoirs have been built in recent years, in part because of environmental opposition and in part because there is little unsubscribed water left. Surface water supplies in the United States have not increased in 20 years, forcing suppliers to pump more groundwater to meet demand. This is bringing the water issue to a head, as groundwater supplies all over the country are declining sharply. According to a report to Congress from the Department of Energy's Energy-Water Nexus Committee, "Some regions have seen groundwater levels drop as much as 300 to 900 feet over the past 50 years because of the pumping of water from aquifers faster than the natural rate of recharge." In the Chicago/Milwaukee area, demand has exceeded precipitation, and groundwater levels are declining as much as 17 feet per year in some locations. In the High Plains, groundwater levels have been reduced by 100 feet; in Houston, by up to 400 feet; and in Tucson/Phoenix, by 300–500 feet. On Long Island, stream flows are declining and salt water is moving inland. Even in the water-rich Pacific Northwest, the groundwater level has declined by 100 feet.

Viewed as a problem of sustainability, the long-term challenge for water supply is to maintain steady growth in living standards without compromising the ability of future generations to meet their own needs and aspirations. Natural waters serve many functions: They provide water supply for domestic and industrial uses; for energy, mining, and transportation; for agriculture; and for recreation. They also supply habitats for wildlife and aquatic life. Sustainability requires keeping these competing needs in balance, managing our water



The degree of water shortage in an area can be defined as the total freshwater withdrawal divided by the available precipitation (precipitation minus evapotranspiration), expressed as a percentage. Freshwater withdrawals already exceed precipitation in many parts of the country, with the most dramatic shortfalls in the Southwest, in the High Plains, in California, and in Florida. (source: Solley et al. / EPRI)



While thermoelectric power generation accounts for roughly 40% of U.S. freshwater withdrawals, much of this volume is used in once-though cooling systems, which return most of the water to the source after use. Thus, power plants actually account for only about 3% of total consumption. (source: Solley et al.)

resources more efficiently and more holistically, finding innovative ways to conserve and recycle water to meet growing demand, keeping water in streams and water bodies to protect the natural environment, and preparing for possible changes in temperature and precipitation from climate change.

Sustainability will require a major reconsideration of our water infrastructure and management practices, according to Bob Goldstein, EPRI's technical executive for water and ecosystems: "Our water infrastructure was designed for a future that is now in our past. We have three major forces driving future water usage and quality—population pressures, environmental protection, and uncertainty about future climate—and our existing infrastructure and inherited management practices are not based on any of these three. As Yogi Berra once said, 'The future ain't what it used to be.' Consider the Colorado River Compact. It was designed at a time—the early twentieth century—that we now recognize from a historical perspective to have been an extremely wet era in terms of runoff. You total the existing allocations and the sum is greater than the river flow."

According to the report of the fourth Intergovernmental Panel on Climate Change, precipitation patterns are likely to move northward, and areas prone to drought, such as the Colorado watershed, are likely to become more arid as the twenty-first century progresses. Some hydrologists foresee the snowpack in the Sierra Nevada declining by 25% by 2050, forcing large-scale constraints on water consumption in California. Nobody knows for certain which areas of the country are likely to become substantially wetter or drier, because the predictive capabilities of climate modeling are still too imprecise. Nevertheless, long-term planning is beginning, and it is apparent that moving fresh water over longer distances will be easier than relocating populations, businesses, and industries. This transport will almost certainly require larger regional compacts among multiple jurisdictions to manage watersheds on a shared basis and to help resolve the political complexities of one region's subsidizing another's water demand.

As one of the major users of water, electricity generation will be required to do its part and, given its technical potential, to take a leadership position in water conservation. Far and away the largest use of water by power plants is for cooling—that is, for condensing the steam flowing out of the turbine-generator and using the water to carry the rejected heat into the atmosphere via cooling towers or by using a water body for once-through cooling. Other major uses of water in the power plant include flue-gas scrubbing, ash sluicing, boiler makeup, gas turbine inlet cooling, dust control, and "housekeeping" activities.

Power and Water Issues

Until the early 1970s, most power plants were located next to a sizable body of water or a major river to ensure adequate water for cooling. These plants used once-through cooling, a process that simply borrows the water, uses it to condense the steam from the turbine, and then returns it to the original water body some 20°F warmer. While highly efficient for cooling, the process has the potential for a twofold impact on aquatic life: fish entrainment and impingement at the front end of the process, and thermal discharge at the back end. Newer units have typically employed evaporative cooling towers in a process known as wet cooling, which withdraws less than 5% of the water needed for once-through cooling. As a result, fish entrainment is minimized and thermal discharge significantly reduced. There are, however, potentially significant local and environmental tradeoffs with cooling towers, including discharge of waterborne pollutants used to control scaling and fouling, release of particulates in air emissions, salt drift, noise, and aesthetic issues.

Over 30% (by capacity) of today's fleet of thermoelectric power plants still utilize the once-through cooling process. The result is that power generation accounts for roughly 40% of freshwater withdrawals in the United States—a figure comparable to the withdrawal level of U.S. agriculture—whereas it accounts for only about 3% of the country's water *consumption.* It is critical to recognize, however, that although the once-through plant consumes only a small fraction of the water it withdraws, it needs the withdrawal to operate. Hence, under drought conditions, a generating plant may have to be shut down or severely curtailed in operation because of its inability to withdraw a sufficient amount of water to meet its thermal discharge permit.

According to John Maulbetsch, a cooling systems expert and EPRI consultant, "We increasingly read and hear that water is too precious to waste on cooling power plants. This can be debated. However, we need to realize that power plants can have a major impact on local water availability. A 1000-MW power plant with wet cooling consumes approximately 10,000 gallons of water a minute through evaporation. When this requirement is imposed on a region that already anticipates shortages for agricultural and municipal needs, it is clearly disruptive and the subject of controversy."

In recent times, water has become a more contentious siting issue for power production—notably in the Southwest, but elsewhere as well. In Idaho, for example, two proposed power plants were opposed by local interests because of the impact on a key aquifer. The governor of Tennessee imposed a moratorium on the installation of new merchant power plants because of cooling constraints. In response to these situations, and in some cases to expedite the siting process, some power producers have moved beyond evaporative cooling towers to the newer and more expensive dry-cooling technologies. One of the premier installations of dry cooling is at the 1600-MW Mystic generating station situated on Boston Harbor; the driving concern in this case was the protection of aquatic life, not water availability.

In the future, says Maulbetsch, "The competition for water will require electricity generators to address conservation of fresh water. There are a number of avenues to consider. One is to use dry-cooling and dry-scrubbing technologies. Another is to find innovative ways to recycle water within the power plant itself. A third is to find and use alternative sources of water, including wastewater supplies from municipalities, agricultural runoff, brackish groundwater, or seawater." He points out that all of these approaches alter the economics of power generation. Dry technologies are usually more capital intensive and typically exact a penalty in terms of plant performance, which in turn raises the cost of power generation. On the other hand, if the cost of water increases in response to greater demand, the cost differences between dry and wet technologies will be reduced.

Dry and Hybrid Technologies

More than 60 power generation facilities

The Break-Even Cost of Water

Engineers evaluating the design of a power plant cooling system will typically try to estimate the so-called break-even cost of water—the point where the total lifetime cost of dry cooling equals the total cost of wet cooling. The capital cost of a dry system will typically run four times the cost of a comparable wet system but can be offset by decades of reduced water consumption and the reduced associated costs.

Water costs include the cost of acquisition or purchase, the cost of delivery, and the cost of treatment and discharge or disposal. Each of these costs can vary by an order of magnitude, depending on plant location, water source, and the requirements of the local jurisdiction.

The cost of acquiring water depends on the geographic region and on whether water use is oversubscribed or undersubscribed in the local area. It also depends on whether the water is purchased outright on an annual basis, or whether the user is able to buy the water rights, which entitle the owner to an agreed number of acre-feet of water per year in perpetuity. Water rights law is complex and varies dramatically from state to state, and the cost range is large. In New Mexico, freshwater costs have increased to $70 per acre-foot for plant cooling water. In California, where the cost of water is quite high, plants can pay up to $400 per acre-foot for reclaimed water (90% of freshwater costs).

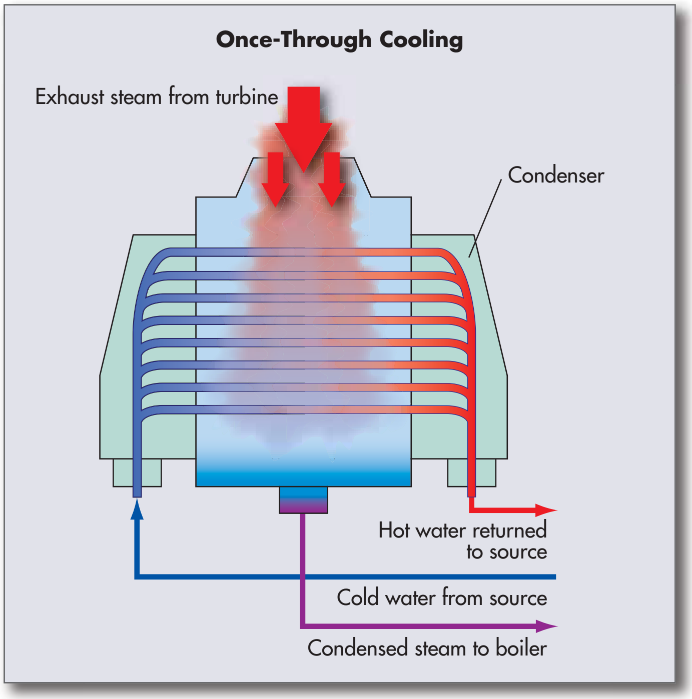
The costs of transporting water from the source to the power plant site include the capital cost of the pipeline and the operating costs for pumping the water. Installation costs are affected by the length of the pipeline and the route. Routes through urban areas can double or triple pipeline costs.

Treatment includes the initial cleanup for in-plant use and preparing the used water for discharge or disposal. Costs are primarily for chemicals, power, maintenance, and labor. The level of treatment required for the disposal of water and/or treatment solids can vary widely; if the plant must operate in a zero-liquid-discharge mode, costs will be at the high end of the range.

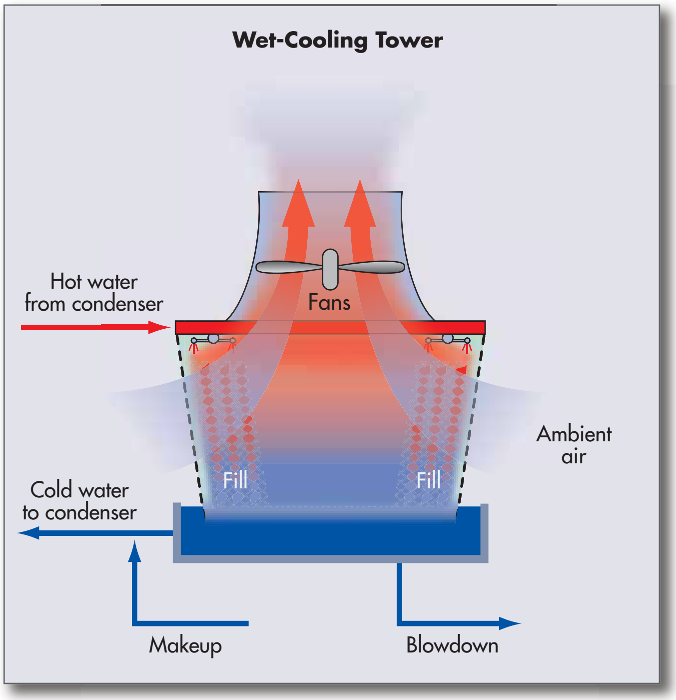
The complete cost picture for water acquisition, delivery, and treatment is shown in the table. The range represents an order-of-magnitude difference between low total cost and high cost. At the extreme, the high cost represents an unlikely combination of negative factors—poor-quality water requiring lengthy uphill pipeline transport to a zero-discharge site. Future costs could be significantly higher.

U.S. Water Costs ($/1000 gal)

	Minimum	Low	Medium	High
Acquisition	<$0.01	$0.05	$0.15	$0.50
Delivery	<$0.01	$0.13	$0.57	$1.20
Treatment/Disposal	$0.10	$0.25	$1.00	$4.00
TOTAL	~$0.10	$0.43	$1.72	$5.70

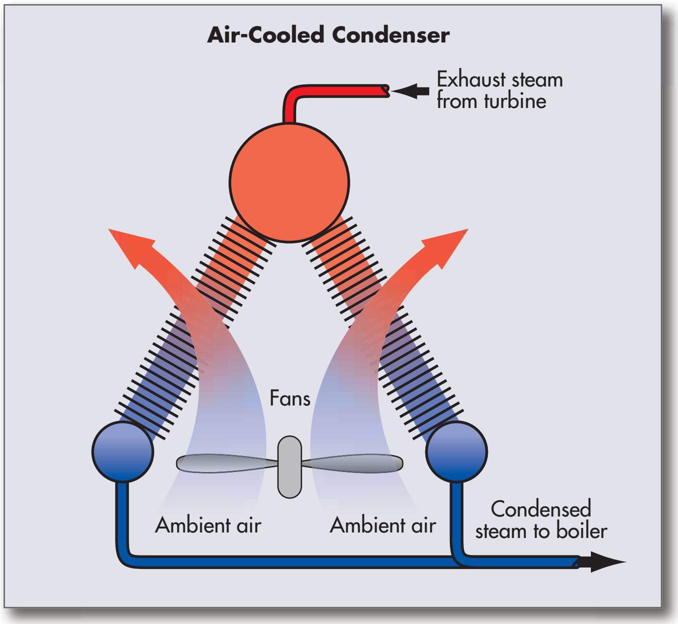


A once-through cooling system takes water directly from a source—a river, lake, or ocean—uses it to condense exhaust steam from the turbine, and then returns the water to the original source about 20°F warmer. Roughly 30% of U.S. thermoelectric capacity still uses once-through cooling.



In a wet-cooling system, hot water from the plant's condenser is piped to the top of a cooling tower, where it flows downward through fill material cooled by ambient air. Addition of makeup water is necessary to replace water lost by evaporation and blowdown.

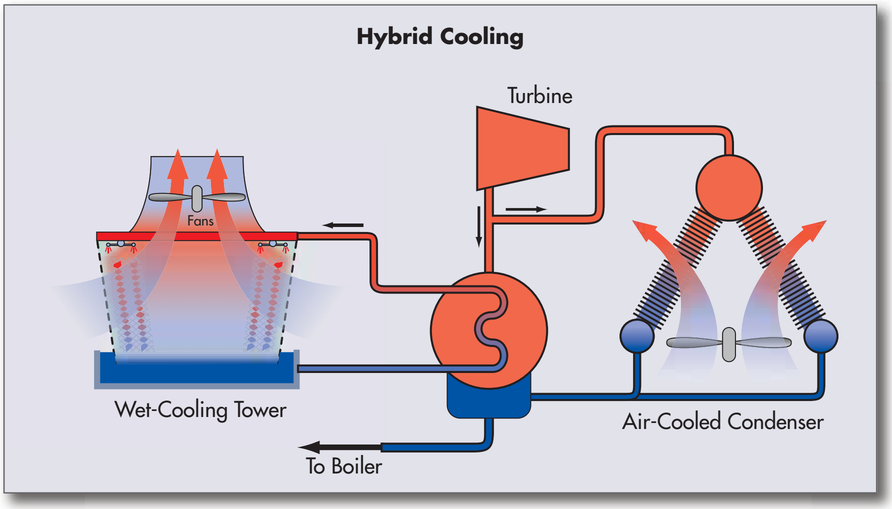
in the United States now use dry cooling in lieu of conventional wet cooling. Most are relatively small units, but there are sizable units (>300 MW) using air-cooled condensers in California, Massachusetts, Nevada, Wyoming, and New York.



Dry-cooled plants feed turbine exhaust steam into the large ducts of an air-cooled condenser. As the steam passes down through the condenser's finned tubes, ambient air blown through the structure condenses it and carries off its heat, working much the same way as a automobile radiator. Dry-cooling systems typically exact a penalty on power plant efficiency.

The principal components of a conventional wet-cooling system are the condenser, the wet tower, and the circulating water system. The turbine exhaust steam flows over the outside of the condenser tubes, where it gives up its heat to the water inside the tubes. The warm water in the tubes is then piped to the cooling tower. From there it flows downward through the packing, or "fill," which is designed to break the water up into small droplets or spread it out into a thin film to maximize the surface area exposed to the cooling air, which is drawn through the tower by a large fan or by natural convection. Evaporation typically carries off 85–90% of the heat, and convection dissipates the remaining 10–15%. Roughly 2% of the cooling water is lost through evaporation, requiring continuous addition of makeup water. Since evaporation results in the buildup of dissolved solids in the circulating water, a portion of the water is discharged as "blowdown" to limit the concentration of these solids and prevent the formation of mineral deposits, which can interfere with the transfer of heat from the condenser to the cooling water.

Where water is at a premium or its use restricted, the major



Hybrid cooling systems, which combine an air-cooled condenser with a wet-cooling tower, can offset the efficiency disadvantage of all-dry systems. The wet system is used only on the hottest days of the year, when dry systems are least efficient. Hybrids can economically reduce the water that would be required by all-wet systems by as much as 80%.

alternative to wet cooling is dry cooling, which uses an air-cooled condenser (ACC). In a dry system, the steam from the turbine is carried in large ducts to the ACC, where the heat is transferred directly to the air passing over the surface. In much the same way cars, refrigerators, and electronics expel their heat, the ACC uses a large number of external fins to increase the surface area exposed to the cooling air.

The ACC is normally designed in the shape of an A-frame, with steam entering along the apex and condensing as it passes downward through finned tubes. There is a key engineering advantage in keeping the steam duct as short as possible to minimize steam pressure losses. As a result, the ACC is normally located near the turbine building itself.

Dry cooling offers distinct advantages in terms of dramatically reducing water consumption while increasing flexibility in power plant siting. The capital cost of dry cooling is considerably higher than that of wet cooling, however, and the dry process typically exacts a penalty on power plant performance on the order of 2% (annual average for an optimized system). For a few hours on the very hottest days of the year, efficiency penalties from dry cooling can rise to more than 20%, requiring more fuel and increasing greenhouse gas emissions.

The capital and operating cost disadvantage of dry cooling can be partially offset, however, by the elimination of most water-related costs. These include the costs of acquisition, delivery, treatment, and discharge and the cost of fish and marine life protection. Sometimes it is not the cost or availability of water that is driving the decision to choose dry cooling, but rather licensing delays because of concerns of the community or agency over competing uses of water.

The capital costs of cooling systems are specific to the size and type of plant, but the installation of dry cooling can cost more than four times that of wet cooling in hot, arid regions, dropping to a factor of three in regions with cooler climates. This is because dry systems are more inefficient in hotter climates. For example, the capital cost of a dry-cooling system for a 500-MW combined-cycle plant could run $21 million to $26 million, compared with $6 million to $7 million for a wet-cooling system, depending on the location.

Wet- and dry-cooling systems can be combined into hybrid systems to gain the advantages of both and offset the disadvantages of each. A hybrid system can be used, for example, to substantially reduce the makeup water consumed in wet cooling without incurring the large increases in heat rate (and thus decreases in generating capacity) associated with all-dry systems. The capital costs tend to fall midway between the all-dry and all-wet systems.

Hybrid systems designed for maximum water conservation are essentially dry systems with just enough wet-cooling capability to prevent significant deterioration in power plant efficiency during the hottest days of the year. Sometimes these systems are referred to as dry/wet-peaking cooling tower systems. When temperatures rise, the wet-cooling system is turned on, improving heat rates and generation capacity. These systems can economically reduce the amount of water that would be required by all-wet systems by as much as 80%.

In-Plant Conservation

The ongoing drive to conserve water has been extended to a wide variety of innovative processes to recover, recycle, and reuse the water already in use in the power plant. This approach calls for treating the water to isolate and remove the contaminants that invariably build up as the plant systems and subsystems perform their functions, and sending the recovered water back into use. The goal is to reduce the amount of fresh water required for makeup at the front end and to reach a point of minimized water use or even zero discharge at the back end.

Different uses in the plant have different requirements for the purity of the water. Maulbetsch says, "In general, if water is to be treated for reuse, it is preferable to treat it completely for the highest level of use and then let the water cascade down to lower-quality uses, rather than clean it up just a little bit for an intended intermediate use."

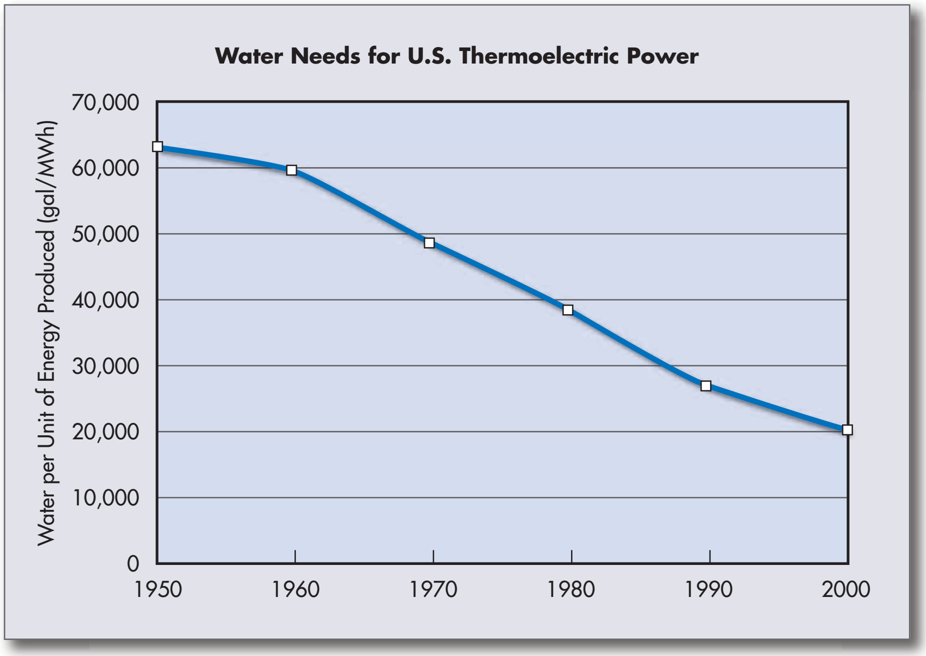
He points to one of the most highly integrated water-recycling operations, now in use at Public Service of New Mexico's San Juan generating station in the Four Corners area. Six streams of wastewater exit the plant and go through multipronged treatment before reentering operations.

Boiler feedwater requires the highest quality, and the wastewater used for this process goes through both distillation and demineralization processes before heading off to the boiler. The intermediate-quality distilled water is sent to the cooling tower. And the lowest-quality water is sent directly from the wastewater pond to the limestone preparation operation. With this integrated process, 97.5% of the water consumed is evaporated in the tower or goes up the stack; less than 1% ends up in the evaporation pond for disposal.

Comparable technologies are being developed for conserving the water used for flue gas scrubbing and ash handling, and more-experimental techniques are expected to recapture some of the water exiting in the cooling tower plume or escaping up the stack. In the traditional operation of a flue gas scrubber, the sulfur dioxide is removed from the flue gas by spraying a limestone slurry into the gas stream. The SO_2 reacts with the calcium in the slurry to form calcium sulfate or sulfite, which falls to the bottom as a wet solid. Some of the water is separated out in a recycle tank and sent back to the scrubber; some is lost through evaporation up the stack; and the remainder stays with the wet solids, which are either landfilled or used commercially for materials such as gypsum wallboard.

One option for reducing the amount of water lost through traditional scrubbing involves cooling the flue gas before scrubbing. Reducing the stack gas temperature by 25°F can reduce evaporative losses by 15–20%. Another option for some plants is an alternative SO_2 dry-scrubbing process in which an alkaline reagent is atomized and sprayed into the hot flue gas to absorb the SO_2. About 20% less water is used in this process than in wet scrubbing, and the residue comes out as a dry product that is airborne, rather than as a wet solid. The dry material in the flue gas is captured by a particulate control device, typically a baghouse.

Dry cooling has obvious advantages in water-constrained regions but may be a good choice elsewhere as well. For example, the Mystic generating station on Boston Harbor chose a dry system over once-through cooling to avoid concerns over possible impacts on aquatic life.



The efficiency of U.S. water use has improved substantially over the last half century. While the volume of water withdrawn for power plant needs has increased by a factor of 5 since 1950, the amount of power generated has grown even faster—by a factor of 15. As a result, the water withdrawn per megawatthour has decreased by more than two-thirds. (source: Limno-Tech, Inc.)

Alternative Sources of Water

Alternative water supplies offer significant opportunities for power plants to limit their use of fresh water. Potential sources include municipal effluent, wastewater from industrial operations, water brought up by oil and gas production, and agricultural runoff, as well as brackish groundwater and seawater. According to the Department of Energy, "With wastewater reclamation and desalinization growing at rates of 15% and 10%, respectively, nontraditional water consumption could well equal freshwater consumption in the U.S. within 30 years."

Municipal wastewater undergoes extensive treatment in the 25,000 municipal effluent facilities in the United States. Typically, the treated water is then discharged into waterways or allowed to percolate in disposal ponds. Only about 8% of the 32 billion gallons per day (BGD) of treated "gray water" is reclaimed or recycled. Gray water represents one of the largest untapped resources of relatively clean water for the future, and its use is projected by DOE to grow from 2.6 BGD in 2006 to 12 BGD by 2015.

Mike DiFilippo, a recognized power industry water chemist, says that municipal wastewater was first used for power plant cooling over 40 years ago. "Initially, only a few plants in California, Texas, and Florida used municipal effluent for cooling," he says. "But in the past 10 years, the use of this resource has increased dramatically, and hundreds of plants are using municipal effluent today. There are several zero-discharge or near-zero-discharge plants using municipal effluent in the Southwest." Zero liquid discharge (ZLD) plants have no water discharge to a receiving water body.

DiFilippo points out that the technical and economic issues in using municipal wastewater vary by plant and location: "Depending on the plant and the final disposition of the plant's wastewater stream, the use of municipal effluent can be relatively simple. At plants where municipal effluent is used in lieu of fresh water and where cooling tower blowdown can be discharged directly, municipal effluent is often incorporated easily into plant operations. In these scenarios, the plant metallurgy must be compatible with the treated effluent. At ZLD plants, municipal effluent is generally more costly to use, but this depends on the freshwater source."

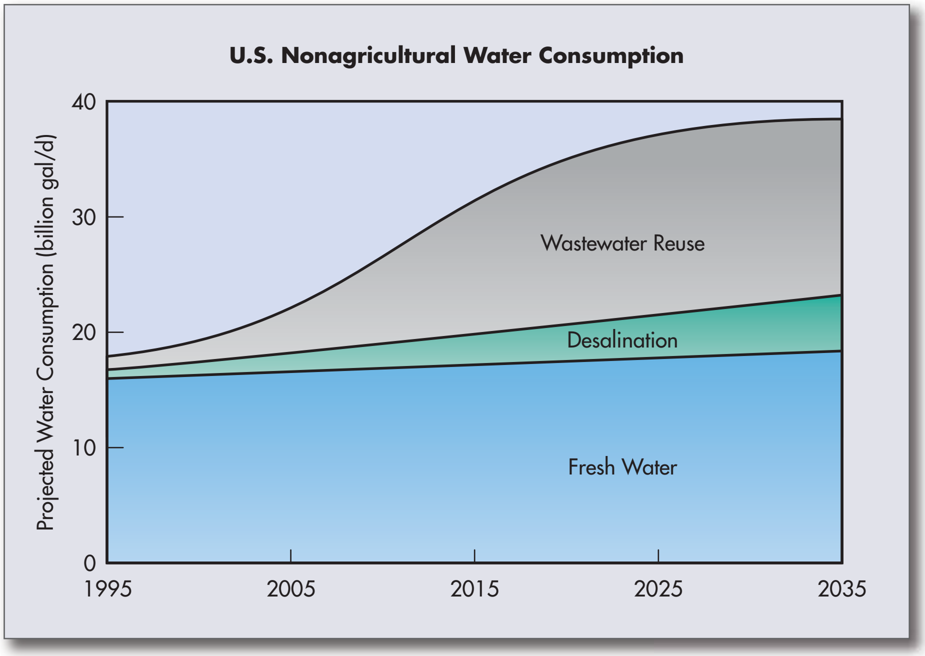
Some of the pioneers in using municipal wastewater include Burbank Power and the Delta Energy Center in California, Southwestern Public Service in Texas, Lakeland Electric in Florida, Public Service Electric and Gas in New Jersey, AES Granite Ridge in New Hampshire, and the Palo Verde nuclear generating station in Arizona.

At Palo Verde, gray water has been used for cooling the three-unit, 3875-MW plant for over 20 years. The gray water is pumped 35 miles from Phoenix, put through an additional (tertiary) stage of treatment, and then stored in a large (760-million-gallon) lined reservoir. The treatment process is elaborate. Effluent is put through trickling filters to reduce ammonia content and adjust alkalinity. Clarifiers are used to remove phosphates and magnesium. Chemicals are used to reduce the level of calcium carbonate, which otherwise would tend to cause a buildup of scale. Finally, gravity filters are used to remove any remaining suspended solids.

There are large brackish groundwater aquifers throughout much of the interior United States. Texas alone, for example, has an estimated 2.5 billion acre-feet of such water, the equivalent of a thousand-year withdrawal at a level equal to 10% of current U.S. freshwater consumption. Treatment costs can range from $1.50 to $3.00 per 1000 gallons, depending largely on salinity, which varies greatly by region from 1000 parts per million (ppm) to 20,000 ppm. Brackish groundwater can also contain high levels of scale-causing compounds, such as carbonate, sulfate, and silica.

Seawater has been used for power plant cooling for decades along the coasts. Its use today is estimated at around 60 BGD. Salinity levels are quite high but are offset by low levels of carbonate, sulfate, and silica, which cause scaling. The real impediment to future use of seawater is the ecological impacts, including the entrainment and impingement of various organisms at the intake structure, the effects of the thermal effluent streams, and the public's growing desire for industry-free coastlines.

Another option is use of produced water, a byproduct of oil, gas, and mining operations. "On average, a barrel of oil brings up about six barrels of produced water, representing a significant source for the future," says DiFilippo. "The quality varies greatly by region and by local geology, with salinity levels ranging from 500 ppm to over 400,000 ppm. Produced water can also have high levels of organics and soluble hydrocarbons, and water from mining operations may contain heavy metals and naturally occurring radioactive materials."



Alternative water supplies offer significant opportunities for power plants to limit their use of fresh water. Nonagricultural water consumption is expected to double in the next 30 years, and most of the increase will come from treated wastewater. (source: DOE)

R&D Priorities

The U.S. power industry and our entire society are facing more and more pressure to use less and less water. According to Bob Goldstein, "As a society, we should manage this issue proactively, intensively, and in an integrated manner. A key is to approach the issues not only on a facility-by-facility basis—a power plant, a municipal treatment center, a bottling plant—but also holistically, recognizing that water is a shared community resource. Every sector of the economy and society has a stake in sustainable water use."

Goldstein points out that whether the industry pursues water management proactively or reactively, it still needs the tools that science and technology can provide. EPRI is developing a comprehensive $35 million R&D strategy based on business and economic considerations for the power industry. The strategy includes five primary elements:

- Developing and applying an engineering and economic framework for evaluating new water-conserving power plant technologies
- Improving dry and hybrid cooling technologies
- Reducing water losses in cooling towers
- Effectively using degraded water sources for plant operations
- Developing water resource assessment and management decision support tools

One key element of the strategy is to reduce the hot-weather loss of cooling efficiency for air-cooled condensers. A second is to recapture water now lost as vapor from cooling towers. A third is to build a decision support framework for water management that takes into account the physical flow of water throughout an entire watershed; this would be an extension of EPRI's pioneering work in watershed assessment and management with respect to acid rain, eutrophication, and bioaccumulation of mercury in fish.

Goldstein envisions that EPRI will implement the power industry's R&D strategy through partnering with government entities and other stakeholder groups.

The Palo Verde nuclear generating station near Phoenix has been using treated municipal effluent—so-called gray water—to meet its plant cooling needs for over 20 years. The effluent is stored on-site in a 760-million-gallon lined reservoir.

Over the last several years, EPRI has published a dozen reports resulting from its studies of electric power and water sustainability. A significant portion of this work was cofunded by DOE, the California Energy Commission, and EPRI's Technology Innovation Program. EPRI has also worked closely with the national energy laboratories on the Energy-Water Nexus Report to Congress, the Energy-Water Nexus Research Roadmap, and the ZeroNet Research Initiative and has collaborated with Electricité de France on creating and testing risk management tools to address the impacts of climate change on water availability for electric power generation.

This year, a new study—with the support of EPRI's Technology Innovation Program; EPRI's Environment, Generation, and Nuclear sectors; and Electricité de France—will examine the application of air-cooled condensers to nuclear plants, the coupling of an ammonia cycle to a steam cycle to increase water-use efficiency, and the means of reducing wind interference with the operation of dry-cooling towers.

The U.S. electric power industry, in partnership with EPRI, is at the forefront of addressing the issue of managing water at its facilities. It has pioneered the use of alternative sources of water, designed and operated plants that minimize water use, and where practical, employed the use of dry and hybrid systems for cooling. In the face of growing national demands for fresh water, the power industry will continue to pursue its commitment to reducing water consumption.

This article was written by Brent Barker. Background information was provided by Robert Goldstein (rogoldst@epri.com) and John Maulbetsch (maulbets@sbcglobal.net).

Further Reading

Energy Demands on Water Resources: Report to Congress on the Interdependency of Energy and Water. U.S. Department of Energy. December 2006.

Program on Technology Innovation: Water Resources for Thermoelectric Power Generation. EPRI. 2006. Report 1014487.

"Evaluation of the Sustainability of Water Withdrawals in the United States, 1995 to 2025." Sujoy B. Roy, Paolo Ricci, et al. *Journal of the American Water Resources Association,* October 2005, 1091–1108.

Air-Cooled Condenser Design, Specification, and Operation Guidelines. EPRI. 2005. Report 1007688.

Comparison of Alternate Cooling Technologies for U.S. Power Plant Cooling Water Systems. EPRI. 2004. Report 1005358.

Technology at Work

Member applications of EPRI science and technology

EPRI Helps KCP&L Improve Transformer Management

Kansas City Power & Light is facing a challenge common to many utilities: managing fleets of aging substation transformers that were installed during the 1960s and 1970s and are approaching the end of their design life. During the '80s and '90s, the failure rates of these "boomer generation" transformers were low and predictably steady from year to year. With advancing age, however, the transformer fleet's failure rate has become more difficult to predict and thus more of a challenge for allocating resources and making sound decisions about repair and replacement. KCP&L sought a fresh approach to managing its aging transformer fleet—an approach that would offer a better way to predict failures, maximize return on investment, and help develop business cases to illuminate the costs and benefits of transformer management options. Chris Kurtz, KCP&L's manager of substation construction and maintenance, found the approach he was looking for in a supplemental project offered by EPRI's Substations Program.

The project's first phase aimed to improve the accuracy of transformer failure prediction. Researchers analyzed data for a 50-MVA dual-winding unit, one of KCP&L's standard transformers for area supply substations. The data included the transformer manufacturer, the date of manufacture, and operating data such as loading records, maintenance history, diagnostic test results, location, and age at time of failure. The project team then used the data to formulate and feed a probabilistic model that predicted future failure rates for that specific class of transformer. The results included the probable lifespan of units that had already failed and been repaired—an important piece of information, since KCP&L commonly opted to repair transformers rather than go with the higher-cost option of purchasing a brand-new unit.

Phase one demonstrated the feasibility and potential of this approach. Early modeling showed, for example, that the lifespan of a repaired transformer is much shorter than that of a new transformer. What was still needed, however, was the capability to use this approach to develop business cases that would provide a quantitative basis for transformer management decisions. To that end, phase two of the project refined the mathematical models and expanded them to include a second class of transformer, a 30-MVA single-winding design that is KCP&L's current standard. The project team then combined the failure prediction modeling with financial analysis to evaluate several strategies: continuing the present practice of rebuilding failed transformers, replacing all failed units with transformers of improved design, proactively replacing existing rebuilt units, and using diagnostics or other means to facilitate life extension.

The study showed that replacing failed transformers with a new design was clearly the preferred option, resulting in far fewer failures and projected savings of $7 million to $15 million, depending on the interest rate. Moreover, the project team was surprised to learn that the preferred new design was not an improved 30-MVA single-winding transformer, but rather a new 50-MVA single-winding unit that was more compatible with the utility's existing substation facilities. "We're making better business decisions today than we would have if we had not done this project," says KCP&L's Kurtz. "And the study findings came at an opportune time: recent increases in transformer prices would have made the repair option more tempting if the business cases hadn't demonstrated that buying new transformers saves a lot more money in the long run."

A key lesson from the project is that acquiring sufficient transformer data presents a significant technical hurdle. Since most utilities have relatively small populations of the same transformer type, it is difficult to generate statistically valid decision support data. To address this challenge, KCP&L is participating in another EPRI supplemental project to develop an industrywide equipment performance database (IDB) for transformers. The IDB will provide a means of sharing data confidentially among participating utilities to support risk-informed asset management decisions. Drawing on a broad cache of utility experience, the data will be statistically valid and will include equipment design, operational and maintenance history, and failure mode. Decision makers will be able to run analyses on the basis of specific transformer class, make, model, age, application, and risk profile.

The methodology and new database will allow any utility to benefit from KCP&L project results, helping provide a rational, quantitative basis for asset management decisions that improve reliability and benefit the company's bottom line. And as Kurtz points out, the risk characterization methodology is not limited to transformers: "This approach could readily be used for other types of high-dollar assets throughout the utility environment."

For more information, contact Bhavin Desai, bdesai@epri.com.

PSE&G Transfers Experts' Knowledge With EPRI Methodology

Public Service Electric & Gas, like many utilities, is swimming against a demographic tide. Seasoned employees are retiring and taking their knowledge and experience with them. Hiring new workers helps stem the loss of some skilled personnel, but PSE&G is especially concerned about losing the rare, mission-critical knowledge residing in the minds of just a few power system experts. These veteran engineers possess a deep and broad understanding of PSE&G's complex power system—both the equipment installed in the early 20th century and the latest microprocessor-based devices. With their knowledge and historical perspective, these veterans have developed special ways of analyzing and solving problems—ways that are not taught in schools or found in books.

Capturing and transferring such knowledge is inherently difficult, and commonly used approaches are seldom effective. Training and mentoring, for example, take years, and such person-to-person transfer doesn't make knowledge broadly accessible or preserve it for future generations. Unstructured attempts at knowledge capture—such as asking departing experts to write down what they know—typically fail to impart the decision processes that experts use when evaluating complex technical problems.

PSE&G turned to EPRI's Human Performance Technology Program to find a more effective way to preserve such knowledge and make it widely available to company personnel. The EPRI program has developed tools and a unique streamlined process for achieving just this end. The process has three steps: it identifies the knowledge to be captured, it determines which tools in the extensive toolbox would be the most effective at capturing the identified expertise, and it uses the tools to create knowledge modules that can be easily transferred to others.

EPRI worked with PSE&G to apply the process to capture the specialized knowledge of retiring experts in the areas of system protection and pipe-type cables.

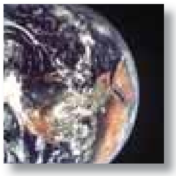
After identifying PSE&G's expectations and objectives, the EPRI team met with each expert in a series of structured interview sessions to elicit their knowledge and identify additional knowledge resources. The team also interviewed the prospective users of the captured knowledge to determine their actual needs.

The interview sessions helped illuminate the knowledge transfer challenges in each area. The system protection expert, for example, had an intimate historical understanding of the system's relay protection scheme and drew upon that knowledge when troubleshooting or analyzing events. Thus, the knowledge modules the EPRI team developed for this area included both text—an overview of asset management functions and an "analysis of events" document that describes the expert's thought processes—and an Excel spreadsheet matrix that includes relay protection schemes, types of equipment protected, and voltage levels, as well as historical information for specific protection schemes.

For the pipe-type cable case, the expert had a "big-picture awareness" of the PSE&G underground transmission network that enabled him to diagnose problems with an accuracy that eluded less-experienced operators. To capture this capability, the team developed a series of concept maps—graphical representations of knowledge that depict concepts and the relationships among them. The concept maps represent the big-picture perspective and outline step-by-step thought processes for diagnosis that senior experts had acquired over many years of experience with the PSE&G underground transmission system.

PSE&G is in the process of placing these knowledge modules on the company's intranet to provide field personnel with fast access to expert information that will help them solve problems. The company intends for the new knowledge web sites to be live, working documents that PSE&G engineers will continually populate with new knowledge as it is obtained.

For more information, contact David Ziebell, dziebell@epri.com.



International

Energy developments around the globe

Nuclear Research Priorities for the Twenty-First Century

The perspective that international members bring to EPRI strengthens the value, scope, and applicability of nuclear research activities and provides insight into new research directions that have global impact. As part of this evolving international collaboration, EPRI and Electricité de France (EDF) jointly hosted EPRI's Nuclear Power Council (NPC) meeting in Paris in early June.

The meeting's main purpose was to discuss global research priorities related to nuclear energy, enabling senior executives to step away from day-to-day tactical concerns and focus on long-term strategies to support nuclear expansion. The meeting included representatives from more than 30 utilities responsible for operating the majority of nuclear plants in the United States, Europe, South America, Africa, and Japan.

Material and Component Performance

During the meeting, NPC participants concluded that continued long-term performance excellence will require the development and deployment of robust predictive tools that are based on improved understanding of fundamental degradation mechanisms. In particular, utilities emphasized the need for monitoring and forecasting tools to guide detection, repair, and/or replacement decisions.

Acute issues that would benefit from additional R&D include stress corrosion cracking, transformer failures, thermal fatigue, and high-cycle fatigue. Chronic issues include boric acid corrosion of steel, electric cable aging, underground piping corrosion, concrete aging, embrittlement in cast stainless steel, and component obsolescence.

Workforce Challenges

NPC participants discussed the difficulty of maintaining high plant performance levels while replacing a large proportion of existing staff and concurrently educating and training the necessary workforce to support new construction. EDF, for example, expects to replace 36% of its workforce over the next seven years—a turnover of more than 9000 people.

NPC participants offered several solutions: developing technologies that reduce plant staffing but may require new skill sets, using R&D activities to attract young people to the nuclear field to complete their education and initiate training, improving the capture and transfer of expert knowledge, and enhancing interactions with universities and technology institutes to promote nuclear energy to prospective engineers and skilled craft workers. Employing a combination of these options is seen as the best approach, with the most-effective choices differing from country to country.

Fuel Reprocessing

Presentations during the NPC meeting addressed key technical issues associated with fuel cycles, both open (spent fuel storage and repositories) and closed (fuel reprocessing and breeder reactors). Critical considerations included the availability of uranium, the retrievability of fuel from repositories, the matching of spent fuel management with commercial reactor deployment strategies, and public acceptance. Participants proposed that an independent review of reprocessing and storage technologies be undertaken to quantify the associated risks and costs.

Advanced Nuclear Reactor Designs

Advanced nuclear reactor designs—such as the Generation IV reactors proposed for commercialization in 20 to 40 years—feature a number of attractive capabilities: enhanced safety systems, minimal waste generation, proliferation resistance, and for some designs, compatibility with process heat recovery and hydrogen production.

While participating governments will continue to be largely responsible for moving Generation IV designs forward, EPRI can provide oversight to ensure that the new designs effectively integrate improvements in passive safety and security features, operating experience (e.g., materials), open licensing, reduced construction time, and advanced fuel designs and cycles.

Common Issues

The NPC meeting reiterated the small-community nature of nuclear power. The high degree of technical complexity and considerable regulatory oversight associated with nuclear energy dictate that plant owners face many issues from a common vantage point. In such an environment, increased international cooperation is critical for all parties, adding perspective that is ultimately converted into technologies and practices of value to the entire community.

The seminar confirmed that EPRI is well positioned to play a leadership role in fostering this cooperation; one particularly important task will be integrating many of the solutions developed for existing nuclear plant problems into improved designs and associated operating and maintenance protocols for new plants before, during, and after the construction process.

Technical Reports & Software

For more information, contact the EPRI Customer Assistance Center at 800.313.3774 (askepri@epri.com). Visit EPRI's web site to download PDF versions of technical reports (www.epri.com).

Environment

Ammonia Impacts on Fly Ash Pond Metals and Toxicity
1012536 (Technical Report)
Program: Mercury Metals and Organics in Aquatic Environments
EPRI Project Manager: Richard Carlton

Effects of Fluctuating Temperatures on Fish Health and Survival
1012545 (Technical Report)
Program: Section 316(a) and 316(b) Fish Protection Issues
EPRI Project Manager: Robert A. Goldstein

Electric Transmission Right-of-Way Post-Blackout Vegetation Management Strategies
1012551 (Technical Report)
Program: Rights-of-Way Environmental Issues in Siting Development and Management
EPRI Project Manager: John Goodrich-Mahoney

ROW 2.0—Right-of-Way Environmental Stewardship Bibliographic Database, Version 2.0
1012555 (Software)
Program: Rights-of-Way Environmental Issues in Siting Development and Management
EPRI Project Manager: John Goodrich-Mahoney

Mercury in the Environment
1012572 (Technical Report)
Program: Air Toxics Health and Risk Assessment
EPRI Project Manager: Leonard Levin

EPRI Regional Haze Research
1012575 (Technical Report)
Program: Assessment Tools for Ozone Particulate Matter and Haze
EPRI Project Manager: Naresh Kumar

Application of Dense Non–Aqueous Phase Liquid Containment Barriers at Manufactured Gas Plant Sites
1012588 (Technical Report)
Program: MGP Site Management
EPRI Project Manager: James Lingle

Coal Tar and Bedrock
1012593 (Technical Report)
Program: MGP Site Management
EPRI Project Manager: Andrew Jay Coleman

Hybrid Ion Exchange Material for the Removal of Arsenic From Water
1012603 (Technical Report)
Program: Transmission and Distribution Soil and Water Issues
EPRI Project Manager: Mary E. Mclearn

Program on Technology Innovation: A New Dosimetric Basis for RF Exposure Compliance Assessment
1013312 (Technical Report)
Programs: EMF Health Assessment and RF Safety; Technology Innovation
EPRI Project Manager: Robert I. Kavet

Field Evaluation of the Comanagement of Utility Low-Volume Wastes With High-Volume Coal Combustion By-Products: LS Site
1014050 (Technical Report)
Program: Coal Combustion Products—Environmental Issues
EPRI Project Manager: Kenneth J. Ladwig

Program on Technology Innovation: Economic Analysis of California Climate Initiatives—An Integrated Approach
1014641 (Technical Report)
Programs: Global Climate Change Policy Costs and Benefits; Technology Innovation
EPRI Project Manager: Larry J. Williams

Program on Technology Innovation: Water Quality Trading Program for Nitrogen
1014646 (Technical Report)
Programs: Watershed Management and Water Resource Sustainability; Technology Innovation
EPRI Project Manager: Jessica Anne Fox

LARK-TRIPP RY2006, Version 1.0
1014695 (Software)
Program: PISCES—Plant Multimedia Toxics Characterization
EPRI Project Manager: Naomi Lynn Goodman

MANAGES 3.0 Demo, Groundwater Data Management and Evaluation Software, Version 3.0
1014711 (Software)
Program: Groundwater Protection and Coal Combustion Products Management
EPRI Project Manager: Kenneth J. Ladwig

Program on Technology Innovation: Evaluation of the Scientific Evidence for a Toxicological Interaction Between Lead and Methylmercury
1014727 (Technical Report)
Programs: Air Toxics Health and Risk Assessment; Technology Innovation
EPRI Project Manager: Leonard Levin

Case Studies in Ash Pond Management, Volume 2
1014752 (Technical Report)
Program: Integrated Facilities Water Management
EPRI Project Manager: Richard Carlton

Assessment of Waterpower Potential and Development Needs
1014762 (Technical Report)
Program: Hydropower Environmental Issues
EPRI Project Manager: Douglas A. Dixon

Structural Steel Attenuation of External Magnetic Fields in Buildings
1014858 (Technical Report)
Program: EMF Health Assessment and RF Safety
EPRI Project Manager: Robert I. Kavet

Electric Energy Industry Workforce: Trends in Motor Vehicle Crashes
1014880 (Technical Report)
Program: Occupational Health and Safety
EPRI Project Manager: Gabor Mezei

Generation

FAST 1.0—Flow Path Analysis for Steam Turbines, Version 1.0
1004565 (Software)
Program: Steam Turbines, Generators, and Balance-of-Plant
EPRI Project Manager: Alan Joseph Grunsky

Understanding Mercury Chemistry Via NEA Model: Summary Results
1010352 (Technical Report)
Program: Integrated Environmental Controls (Hg, SO$_2$, NO$_x$, and Particulate)
EPRI Project Manager: George R. Offen

Guidelines for New High-Reliability Fossil Plants
1012203 (Technical Report)
Program: Boiler and Turbine Steam and Cycle Chemistry
EPRI Project Manager: Barry Dooley

Development of Model to Predict Stress Corrosion Cracking and Corrosion Fatigue of Low-Pressure Turbine Components
1012204 (Technical Report)
Programs: Boiler and Turbine Steam and Cycle Chemistry; Steam Turbines, Generators, and Balance-of-Plant
EPRI Project Manager: Barry Dooley

Development of Steam Phase Sensors
1012206 (Technical Report)
Programs: Boiler and Turbine Steam and Cycle Chemistry; Steam Turbines, Generators, and Balance-of-Plant
EPRI Project Manager: Barry Dooley

Boiler Water Deposition Model for Fossil-Fueled Power Plants
1012207 (Technical Report)
Program: Boiler and Turbine Steam and Cycle Chemistry
EPRI Project Manager: Kevin Shields

Fossil Plant Cycle Chemistry Instrumentation and Control—State-of-Knowledge Assessment
1012209 (Technical Report)
Program: Boiler and Turbine Steam and Cycle Chemistry
EPRI Project Manager: Barry Dooley

Simulated Boiler Corrosion Studies Using Electrochemical Techniques
1012210 (Technical Report)
Program: Boiler and Turbine Steam and Cycle Chemistry
EPRI Project Manager: Barry Dooley

Guidelines for Reducing the Time and Cost of Turbine-Generator Maintenance Overhauls and Inspections 2006
1012212 (Technical Report)
Program: Steam Turbines, Generators, and Balance-of-Plant
EPRI Project Manager: Alan Joseph Grunsky

Automated Control System Tuning Demonstration
1012254 (Technical Report)
Program: I&C and Automation for Improved Plant Operations
EPRI Project Manager: Aaron James Hussey

Large-Particle Ash Mitigation Methods
1012660 (Technical Report)
Program: Post-Combustion NO_x Control
EPRI Project Manager: David R. Broske

2006 Workshop on Selective Catalytic Reduction
1012665 (Technical Report)
Program: Post-Combustion NO_x Control
EPRI Project Manager: David R. Broske

EPRIswitch and Other State-of-the-Art Power Supplies and Controllers for ESPs
1012682 (Technical Report)
Program: Particulate and Opacity Control
EPRI Project Manager: Ralph F. Altman

Electrostatic Precipitator Performance Modeling of High-Carbon Ash Using EPRI's ESPM
1012685 (Technical Report)
Program: Particulate and Opacity Control
EPRI Project Manager: Ralph F. Altman

Continuous Mercury Monitoring Guidelines
1012691 (Technical Report)
Program: Continuous Emissions Monitoring
EPRI Project Manager: Charles E. Dene

MIE 1.0—Gas Turbine Maintenance Interval Estimator, Version 1.0
1012702 (Software)
Program: Combustion Turbine (CT) and Combined-Cycle (CC) O&M
EPRI Project Manager: Leonard C. Angello

Gas Turbine Overhaul Plan (GTOP) for 11N2, Version 1.0
1012711 (Software)
Program: Combustion Turbine (CT) and Combined-Cycle (CC) O&M
EPRI Project Manager: John R. Scheibel

CTCC O&M Cost Analyzer 6.0—Combustion Turbine/Combined-Cycle Operations and Maintenance Cost Analyzer, Version 6.0
1012717 (Software)
Program: New Combustion Turbine/Combined-Cycle Design, Repowering, and Risk Mitigation
EPRI Project Manager: Dale S. Grace

Renewable Energy Technical Assessment Guide: TAG-RE—2006
1012722 (Technical Report)
Program: Renewable Energy Technology and Strategy
EPRI Project Manager: Charles R. McGowin

Boiler and Heat Recovery Steam Generator Tube Failures: Theory and Practice
1012757 (Technical Report)
Programs: Boiler Life and Availability Improvement; Boiler and Turbine Steam and Cycle Chemistry; Heat Recovery Steam Generator (HRSG) Dependability
EPRI Project Manager: Barry Dooley

Evaluating and Avoiding Heat Recovery Steam Generator Tube Damage Caused by Duct Burners
1012758 (Technical Report)
Program: Heat Recovery Steam Generator (HRSG) Dependability
EPRI Project Manager: Barry Dooley

Guidelines for the Nondestructive Examination of Heat Recovery Steam Generators
1012759 (Technical Report)
Program: Heat Recovery Steam Generator (HRSG) Dependability
EPRI Project Manager: Stan M. Walker

Guidelines for Obtaining and Using Operating Experience at Fossil Power Plants
1012783 (Technical Report)
Program: Operations Management and Technology
EPRI Project Manager: C. Wayne Crawford

Human Performance—Fossil Operations
1012786 (Technical Report)
Program: Operations Management and Technology
EPRI Project Manager: C. Wayne Crawford

Management of Operational Limits
1012788 (Technical Report)
Program: Operations Management and Technology
EPRI Project Manager: C. Wayne Crawford

SOAPP-CT Workstation, Version 8
1013298 (Software)
Program: SOAPP Software
EPRI Project Manager: Dale S. Grace

Demonstration of Automation on a Combined-Cycle Plant
1013344 (Technical Report)
Program: I&C and Automation for Improved Plant Operations
EPRI Project Manager: Aaron James Hussey

FGD Chemistry and Analytical Methods Handbook
1013347 (Technical Report)
Program: Integrated Environmental Controls (Hg, SO_2, NO_x, and Particulate)
EPRI Project Manager: Charles E. Dene

The Grades 11 and 12 Low-Alloy Steel Handbook
1013358 (Technical Report)
Program: Fossil Materials and Repair
EPRI Project Manager: David W. Gandy

Main Generator Rotor Maintenance
1013458 (Technical Report)
Program: Steam Turbines, Generators, and Balance-of-Plant
EPRI Project Manager: Jan Stein

Plant Guide to Turbine Disk Rim Inspection
1013459 (Technical Report)
Program: Steam Turbines, Generators, and Balance-of-Plant
EPRI Project Manager: Paul Zayicek

Torsional Interaction Between Electrical Network Phenomena and Turbine-Generator Shafts
1013460 (Technical Report)
Program: Steam Turbines, Generators, and Balance-of-Plant
EPRI Project Manager: Jan Stein

Turbine Overspeed Trip Modernization
1013461 (Technical Report)
Program: Steam Turbines, Generators, and Balance-of-Plant
EPRI Project Manager: Stephen H. Hesler

Turbine-Generator Auxiliary Systems, Volume 2: Turbine Steam Seal System Maintenance Guide
1013462 (Technical Report)
Program: Steam Turbines, Generators, and Balance-of-Plant
EPRI Project Manager: Alan Joseph Grunsky

Hydropower to Hydrogen: Feasibility Study
1014383 (Technical Report)
Program: Hydrogen-Electric Economy
EPRI Project Manager: David Thimsen

Proceedings: Impacts of Fuel Quality on Power Production
1014551 (Technical Report)
Program: Combustion Performance and NO_x Control
EPRI Project Manager: David C. O'Connor

Small-Scale, Biomass-Fired Gas Turbine Plants Suitable for Distributed and Mobile Power Generation
1014594 (Technical Report)
Programs: Coal Fleet for Tomorrow—Future Coal Generation Options; Renewable Energy Technology and Strategy
EPRI Project Manager: John Wheeldon

SOAPP-CT O&M Cost Estimator, State-of-the-Art Power Plant Combustion Turbine/Combined-Cycle Operations and Maintenance Cost Estimator, Version 3.5
1014612 (Software)
Program: SOAPP Software
EPRI Project Manager: Dale S. Grace

Carbon Steel Handbook
1014670 (Technical Report)
Program: Fossil Materials and Repair
EPRI Project Manager: David W. Gandy

State-of-Knowledge Assessment of Residual Oil Nickel Emissions
1014691 (Technical Report)
Program: Combustion Performance and NO_x Control
EPRI Project Manager: Anthony Facchiano

Coal Distribution Assessment at Martin Lake Unit 1
1014723 (Technical Report)
Program: Combustion Performance and NO_x Control
EPRI Project Manager: Jose C. Sanchez

Guidelines for Reducing the Time and Cost of Turbine-Generator Maintenance Overhauls and Inspections 2006, Volume 4: Turbine-Generator Component Procurement Specifications
1014729 (Technical Report)
Program: Steam Turbines, Generators, and Balance-of-Plant
EPRI Project Manager: Alan Joseph Grunsky

Guidelines for Reducing the Time and Cost of Turbine-Generator Maintenance Overhauls and Inspections 2006, Volume 1: General Practices
1014730 (Technical Report)
Program: Steam Turbines, Generators, and Balance-of-Plant
EPRI Project Manager: Alan Joseph Grunsky

Guidelines for Reducing the Time and Cost of Turbine-Generator Maintenance Overhauls and Inspections 2006, Volume 5: Directory and Engineering Database for Large Steam Turbines
1014731 (Technical Report)
Program: Steam Turbines, Generators, and Balance-of-Plant
EPRI Project Manager: Alan Joseph Grunsky

CatReact, Version 1.1a
1014740 (Software)
Program: Post-Combustion NO_x Control
EPRI Project Manager: David R. Broske

Program on Technology Innovation: Detection of Circumferential Cracking in Weld Overlays on Boiler Tubes
1014741 (Technical Report)
Programs: Combustion Performance and NO_x Control; Technology Innovation
EPRI Project Manager: Jose C. Sanchez

2007 EPRI Heat Rate Improvement Conference Proceedings
1014799 (Technical Report)
Program: Combustion Performance and NO_x Control
EPRI Project Manager: Jeffrey Stallings

Program on Technology Innovation: Redesign of the Alden/Concepts NREC Helical Turbine for Increased Power Density and Fish Survival
1014810 (Technical Report)
Programs: Hydropower Environmental Issues; Hydropower Emerging Issues and Technologies; Technology Innovation
EPRI Project Manager: Douglas A. Dixon

Electrochemical Corrosion Potential (ECP) of Hollow Copper Strands in Water-Cooled Generators
1014813 (Technical Report)
Program: Steam Turbines, Generators, and Balance-of-Plant
EPRI Project Manager: Jan Stein

Proceedings: Eighth International Conference on Cycle Chemistry in Fossil and Combined-Cycle Plants with Heat Recovery Steam Generators, June 20–22, 2006, Calgary, Alberta, Canada
1014831 (Technical Report)
Programs: Boiler and Turbine Steam and Cycle Chemistry; Heat Recovery Steam Generator (HRSG) Dependability
EPRI Project Manager: Barry Dooley

Biodiesel Co-Firing—Field Demonstration Results
1014844 (Technical Report)
Program: Renewable and Hydropower Generation
EPRI Project Manager: Anthony Facchiano

Nuclear

Verification and Validation of Selected Fire Models for Nuclear Power Plant Applications
1011999 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Robert Kassawara

Automated Eddy Current Data Analysis Software, Version 3.0
1013366 (Software)
Program: Nuclear Power
EPRI Project Manager: James M. Benson

Automated Analysis of Rotating-Probe Eddy-Current Data
1013386 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: James M. Benson

BWRVIP-168: BWR Vessel and Internals Project, Guidelines for Disposition of Inaccessible Core Spray Piping Welds in BWR Internals
1013390 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Robert G. Carter

BWRVIP-169: BWR Vessel and Internals Project, Testing and Evaluation of BWR Supplemental Surveillance Program (SSP) Capsules A, B, and C
1013399 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Robert G. Carter

BWRVIP-170: BWR Vessel and Internals Project—NDE Development 2006
1013405 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Jeff Landrum

BWRVIP-166: BWR Vessel and Internals Project, Report and NRC Correspondence DVD-ROM, Version 12.2006
1013406 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Randal Stark

BWRVIP-172: BWR Vessel and Internals Project, Crack Growth in High-Fluence BWR Materials
1013407 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Rajeshwar Pathania

BWRVIP-154, Revision 1: BWR Vessel and Internals Project, Fracture Toughness in High-Fluence BWR Materials—Progress Report for 2005–2006
1013408 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Anne Genevieve Demma

AREVA Poolside Measurements of BWR Channels in 2005–2006
1013426 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Erik Mader

Spent-Fuel Transportation Applications: Longitudinal Tearing Resulting From Transportation Accidents—A Probabilistic Treatment
1013448 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Albert J. Machiels

Criticality Risks During Transportation of Spent Nuclear Fuel
1013449 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Albert J. Machiels

Assessment of Accident Risk for Transport of Spent Nuclear Fuel to Yucca Mountain Using RADTRAN 5.5
1013450 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: John Kessler

Nondestructive Evaluation: Surface Examination of Nickel Alloy Welds, Phase II
1013451 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Pedro Felipe Lara

Nondestructive Evaluation: Conventional Nozzle Inner Radius Generic Procedure and Modeling Process Report
1013452 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Mark Dennis

Nondestructive Evaluation: Balance-of-Plant Eddy-Current Centralized Certification Program for the Power Industry
1013453 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Jeganathan Maruthamuthu

Nondestructive Evaluation: Enhanced ID Pit Sizing for Heat Exchangers
1013454 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Kenji J. Krzywosz

Nuclear Maintenance Applications Center: Switchgear and Bus Maintenance Guide
1013457 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Wayne Johnson

Nuclear Maintenance Applications Center: Application Guide for Motor-Operated Valves in Nuclear Power Plants, Revision 2 (replaces TR-106563)
1013463 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: John F. Hosler

Plant Support Engineering: Aging and Degradation Survey for Nuclear Service Level I Coatings
1013465 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Timothy Eckert

Nuclear Maintenance Applications Center: Large Flange and Casing Leakage
1013466 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Alan Joseph Grunsky

Nuclear Maintenance Applications Center: Senior Craft Mentoring Skills and On-the-Job Training Guidelines
1013467 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Ray Henson Chambers

Condition Assessment of Large-Diameter Buried Piping, Phase 3—Field Trial
1013468 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Pedro Felipe Lara

Technology for Examination of Boiling Water Reactor Bottom Head Drain Lines
1013469 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Albert J. Machiels

Plant Support Engineering: Guidance for Replacing Heat Exchangers at Nuclear Power Plants With Plate Heat Exchangers
1013470 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Timothy Eckert

Nuclear Maintenance Applications Center: Troubleshooting Skills Development Guidelines
1013471 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: James P. Sharkey

Nuclear Maintenance Applications Center: Guidelines for Addressing Contingency Spare Parts at Nuclear Power Plants
1013472 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: James P. Sharkey

The SmartLeak Sensor: A Novel Self-Powered Clamp-on Flowmeter
1013473 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: John F. Hosler

Investigation Into Flow-Accelerated Corrosion at Low Temperatures
1013474 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Albert J. Machiels

Plant Support Engineering: License Renewal Electrical Handbook
1013475 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Gary John Toman

Plant Support Engineering: Nuclear Plant License Renewal Commitments
1013477 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Neil Wilmshurst

Tensile Testing of Cell Classification 345464C High-Density Polyethylene Pipe Material
1013479 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Albert J. Machiels

Design and Qualification of Cured-in-Place Liners for the Rehabilitation of ASME Safety Class 3 Piping Systems
1013480 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Albert J. Machiels

Alarm Management Requirements Based on Electricité de France Experience
1013483 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Joseph A. Naser

Program on Technology Innovation: Guidance for Selecting, Designing, and Implementing 2.5-D and 3-D Visualization Systems That Benefit Utility Applications
1013484 (Technical Report)
Programs: Nuclear Power; Technology Innovation
EPRI Project Manager: Joseph A. Naser

Revised Guidelines for Wireless Technology in Power Plants
1013485 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Aaron James Hussey

Plant Application of On-Line Monitoring for Calibration Interval Extension of Safety-Related Instruments, Volumes 1 and 2
1013486 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Joseph A. Naser

Equipment Condition Assessment: Cost-Benefit Guidelines
1013487 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Joseph A. Naser

Leading Business Performance Indicators for Nuclear Power Enterprises
1013488 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Stephen Michael Hess

Use of EPRI/NRC-RES Fire Probabilistic Risk Assessment (PRA) Methodology in Estimating Risk Impact of Plant Changes
1013489 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Robert Kassawara

CAFTA 5.2, Demo Version
1014407 (Software)
Program: Nuclear Power
EPRI Project Manager: Frank J. Rahn

Effective Refueling Outage Preparation and Execution Guidance
1014480 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Ray Henson Chambers

Nuclear Maintenance Applications Center: Maintenance Work Package Training for Nuclear Utility Personnel—Student Handbook
1014533 (Technical Report)
Program: Equipment Reliability
EPRI Project Manager: Lee Alvin Rogers

Hot Cell Examination of AREVA M5 PWR Cladding and Assembly Components Irradiated at Ringhals 4 up to 63 GWd/MTU
1014542 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Erik Mader

MULTEQ: Equilibrium of an Electrolytic Solution with Vapor-Liquid Partitioning and Precipitation—The Database, Version 5.0
1014602 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Keith Paul Fruzzetti

Effect of Bending Loads on Leakage Integrity of Steam Generator Tubes
1014660 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Mary Helen Cothron

Impact of Non-Pressure Loads on Leakage Integrity of Steam Generator Tubes
1014661 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Mary Helen Cothron

Operational Strategies to Reduce Class B/C Wastes
1014707 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Sean P. Bushart

PWR Steam Generator Foreign Object Exclusion Systems
1014722 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Mary Helen Cothron

BWRVIP-167: BWR Vessel and Internals Project, Boiling Water Reactor Issue Management Tables
1014753 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Randal Stark

Update on the Tools for Integrity Assessment Project
1014756 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Mary Helen Cothron

Plant Support Engineering: Main Generator End of Life and Planning Considerations
1014783 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Gary John Toman

Graphite Dust Deflagration
1014797 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Christopher Wood

Proceedings: 2006 ASME/EPRI Radwaste Workshop
1014822 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Sean P. Bushart

Proceedings: 2006 EPRI International Low Level Waste Conference and Exhibit
1014823 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Sean P. Bushart

Applicability of the Generic Equipment Ruggedness Spectra (GERS) for Internationally Manufactured Equipment
1014833 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Robert Kassawara

Nondestructive Evaluation: EPRI NDE Program Mockup Catalog
1014843 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Greg Selby

Nondestructive Evaluation: Ultrasonic Examination of Steam Generator Tube Training Guide
1014860 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Steve Kenefick

Braidwood Leaking Fuel Root Cause Hot Cell Investigation
1014864 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Erik Mader

Nondestructive Evaluation: EPRI NDE Program Product Catalog, 2006 Update
1014866 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Greg Selby

BWRVIP-59-A: BWR Vessel and Internals Project, Evaluation of Crack Growth in BWR Nickel Base Austenitic Alloys in RPV Internals
1014874 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Robert G. Carter

Fuel Reliability Project: Boiling Water Fuel Performance at Kernkraftwerk Leibstadt
1014876 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Erik Mader

BWRVIP-173: BWR Vessel and Internals Project, Evaluation of Chemistry Data for BWR Vessel Nozzle Forging Materials
1014995 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Robert G. Carter

BWRVIP-171: BWR Vessel and Internals Project, Evaluation of Effectiveness of On-Line NMCA on IGSCC—Results of the 2006 UT Examination of Core Shroud Indications in the OLNC Reference Plant
1014996 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Rajeshwar Pathania

Fuel Relocation Effects for Transportation Packages
1015050 (Technical Report)
Program: Nuclear Power
EPRI Project Manager: Albert J. Machiels

Power Delivery

Electric Generation Expansion Analysis System, Version 9.02B
1011221 (Software)
Program: Grid Operations and Planning
EPRI Project Manager: Peter Hirsch

Utility Line Inspections and Audits
1012443 (Technical Report)
Program: Power Quality
EPRI Project Manager: Bill Howe

PQDIF Application Guide
1012446 (Technical Report)
Program: Power Quality
EPRI Project Manager: Daniel Sabin

Automated Evaluation of Power System Harmonic Performance
1012447 (Technical Report)
Program: Power Quality
EPRI Project Manager: Daniel Sabin

Industrial Design Guide (IDG), Version 6.10
1012453 (Software)
Program: Power Quality
EPRI Project Manager: Bill Howe

Description of a Basic Vehicle Control Strategy for a Plug-In Hybrid Vehicle
1012460 (Technical Report)
Program: Electric Transportation
EPRI Project Manager: Robert Graham

Plug-in Hybrid Electric Vehicle Data Collection and Analysis Plan
1012462 (Technical Report)
Program: Electric Transportation
EPRI Project Manager: Robert Graham

Energy Consumption and CO_2 Emissions of Plug-In Hybrid Electric Vehicles
1012468 (Technical Report)
Program: Electric Transportation
EPRI Project Manager: Robert Graham

Interoperability Test #9 of the Generic Interface Definition (GID) Standards and the Common Information Model (CIM)
1012494 (Technical Report)
Program: Grid Operations and Planning
EPRI Project Manager: David Becker

Third Power Delivery Asset Management Conference Proceedings
1012497 (Technical Report)
Programs: Power Delivery Asset Management; Enterprise Asset Management
EPRI Project Manager: Jeremy Bloom

Value Modeling and Measuring Key Performance Indices for Power Delivery
1012502 (Technical Report)
Program: Power Delivery Asset Management
EPRI Project Manager: Jeremy Bloom

Information Technology for Enterprise Asset Management
1012527 (Technical Report)
Program: Enterprise Asset Management
EPRI Project Manager: Jeremy Bloom

Communications Security Analysis for Control System Networks: Preliminary Report
1013609 (Technical Report)
Program: Energy Information Security
EPRI Project Manager: Thomas Edward Kropp

Underground Cable Population Model With Testing
1014754 (Software)
Program: Power Delivery Asset Management
EPRI Project Manager: Jeremy Bloom

Improved Thermal Modeling Tools for Substation Equipment
1014789 (Technical Report)
Program: System Approach to Increased Transmission Capacity
EPRI Project Manager: Rambabu Adapa

Hazards of Step, Touch, and Transfer Voltages DVD
1014839 (Technical Report)
Program: Overhead Transmission
EPRI Project Manager: George Gela

EPRI Underground Transmission Systems Reference Book
1014840 (Technical Report)
Program: Underground Transmission
EPRI Project Manager: Steven Eckroad

Development of a Method to Introduce Controlled Amounts of Moisture in PILC Cables
1014868 (Technical Report)
Program: Underground Distribution Systems
EPRI Project Manager: Matthew G. Olearczyk

Ice Bear Energy Storage Demonstration at Hawaii Department of Education Operations and Maintenance
1015190 (Technical Report)
Program: Advancing End-Use Energy Efficiency and Technologies
EPRI Project Manager: Andra Mercedes Rogers

FAD 4.0 (Foundation Analysis and Design Software)
1015204 (Software)
Program: Overhead Transmission
EPRI Project Manager: John Kar Leung Chan

Program on Technology Innovation: Grain Growth in Lead Alloy Sheathing and Its Influence on the Life of Lead-Sheathed Power Cables
1015214 (Technical Report)
Program: Technology Innovation
EPRI Project Manager: Matthew G. Olearczyk

Technology Innovation

Program on Technology Innovation: A New Dosimetric Basis for RF Exposure Compliance Assessment
1013312 (Technical Report)
Programs: EMF Health Assessment and RF Safety; Technology Innovation
EPRI Project Manager: Robert I. Kavet

Program on Technology Innovation: Economic Analysis of California Climate Initiatives—An Integrated Approach
1014641 (Technical Report)
Programs: Global Climate Change Policy Costs and Benefits; Technology Innovation
EPRI Project Manager: Larry J. Williams

Program on Technology Innovation: Water Quality Trading Program for Nitrogen
1014646 (Technical Report)
Programs: Watershed Management and Water Resource Sustainability; Technology Innovation
EPRI Project Manager: Jessica Anne Fox

Program on Technology Innovation: Evaluation of the Scientific Evidence for a Toxicological Interaction Between Lead and Methylmercury
1014727 (Technical Report)
Programs: Air Toxics Health and Risk Assessment; Technology Innovation
EPRI Project Manager: Leonard Levin

Program on Technology Innovation: Detection of Circumferential Cracking in Weld Overlays on Boiler Tubes
1014741 (Technical Report)
Programs: Combustion Performance and NO_x Control; Technology Innovation
EPRI Project Manager: Jose C. Sanchez

Program on Technology Innovation: Redesign of the Alden/Concepts NREC Helical Turbine for Increased Power Density and Fish Survival
1014810 (Technical Report)
Programs: Hydropower Environmental Issues; Hydropower Emerging Issues and Technologies; Technology Innovation
EPRI Project Manager: Douglas A. Dixon

Program on Technology Innovation: The Galvin Path to Perfect Power—A Technical Assessment
1014834 (Technical Report)
Programs: Intelligrid; Technology Innovation
EPRI Project Manager: Stan Rosinski

Program on Technology Innovation: The Galvin Electricity Initiative Microgrid Workshop
1014835 (Technical Report)
Programs: Intelligrid; Technology Innovation
EPRI Project Manager: Clark W. Gellings

Program on Technology Innovation: Sonoluminescence of Nano- and Submicron Bubbles
1014855 (Technical Report)
Program: Technology Innovation
EPRI Project Manager: Kenneth Barry

Program on Technology Innovation: Unleashing Innovation—Metrics for Innovation Management Workshop
1015177 (Technical Report)
Program: Technology Innovation
EPRI Project Manager: Stan Rosinski

Program on Technology Innovation: Grain Growth in Lead Alloy Sheathing and Its Influence on the Life of Lead-Sheathed Power Cables
1015214 (Technical Report)
Program: Technology Innovation
EPRI Project Manager: Matthew G. Olearczyk

EPRI JOURNAL
ELECTRIC POWER RESEARCH INSTITUTE

SUMMER 2007

EPRI | ELECTRIC POWER
RESEARCH INSTITUTE

Post Office Box 10412
Palo Alto, California 94303-0813

ADDRESS SERVICE REQUESTED

NONPROFIT ORGANIZATION
U.S. POSTAGE
PAID
SALEM OR
PERMIT NUMBER 526

Printed on recycled paper in the United States of America

1015362