Building Interest in Wind

ELECTRIC POWER RESEARCH INSTITUTE

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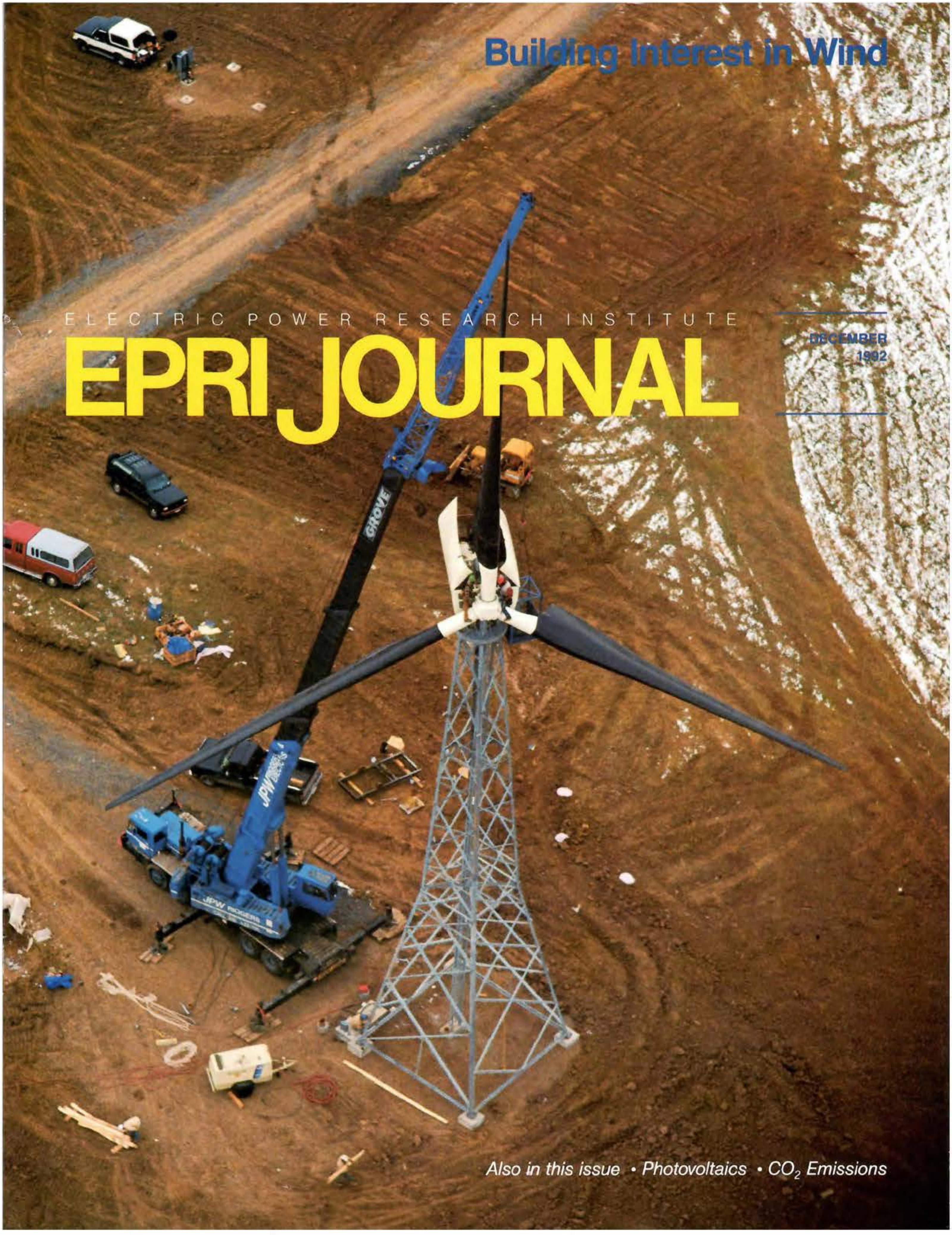

Also in this issue • Photovoltaics • CO_2 Emissions

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Cover: Reflecting a new surge of utility interest in wind power, Niagara Mohawk Power Corporation recently installed two state-of-the-art variable-speed wind turbines near Lake Ontario.

Enlightened and Endless Electricity

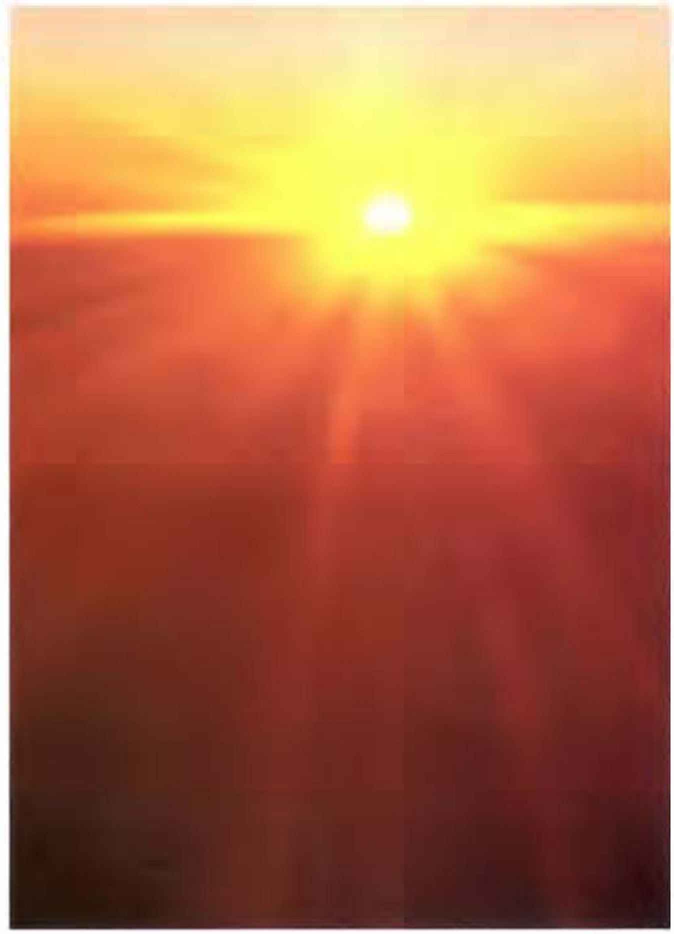
Renewables offer clean and sustainable electricity at costs that are becoming increasingly competitive with those of fossil-derived electricity. However, renewables have been characterized as long on promise and short on delivery. The failures have been highly visible, while the successes have neither made headlines nor become common knowledge. Nevertheless, the government-subsidized, market-driven approach of the eighties led to major advances in technology, particularly for wind turbines. Over the past decade, costs for wind-derived electricity have dropped by a factor of 6, to about 5¢/kWh for sites with very good winds (averaging about 16 miles per hour).

The rush to obtain government subsidies for renewables deployment led to dramatic technology improvements, which were achieved through an Edisonian, trial-and-error approach. Trial and error has its limitations, however, and today major advances require an approach based on fundamental principles. As the two lead articles indicate, this approach is resulting in a new generation of photovoltaic cells and wind power systems that are on the threshold of commercial availability. The development of this new generation of technology was driven by skill and excellence in materials, design, engineering, and electronics. Equally important, as the articles show, perseverance has been a key ingredient of success.

Collaboration among the stakeholders in renewables deployment is emerging as another important ingredient. In fact, a remarkable spirit of cooperation between the U.S. Department of Energy and EPRI provided the basis for a landmark agreement to accelerate the commercialization of the next generation of wind turbines. The resulting Utility Wind Turbine Performance Verification Program will bring together vendors, utilities, DOE, and EPRI to field-test a variety of advanced wind machines in different climates.

While the renewables story is well over a decade old, we're only at the end of the beginning. Opportunities to increase electricity supply, improve service, and expand business are becoming apparent to the visionaries. For example, J. W. Marshall, chairman and CEO of Idaho Power, has recently requested that his state's utility commission provide Idaho Power the opportunity to install, own, and operate photovoltaic systems at the premises of remote customers instead of extending costly distribution lines from the utility grid. Marshall and others have probably asked themselves a few simple questions: Are there business opportunities for cost-effective technologies that are inherently environmentally attractive? Will the public continue to push for renewables deployment? Will corporate image be enhanced by a meaningful renewables program? Marshall's actions indicate his answers. We applaud his leadership in pursuing a strategic path to enlightened and endless electricity.

James R. Birk, Director
Storage & Renewables Department



RESEARCH UPDATE

DEPARTMENTS

EPRI JOURNAL

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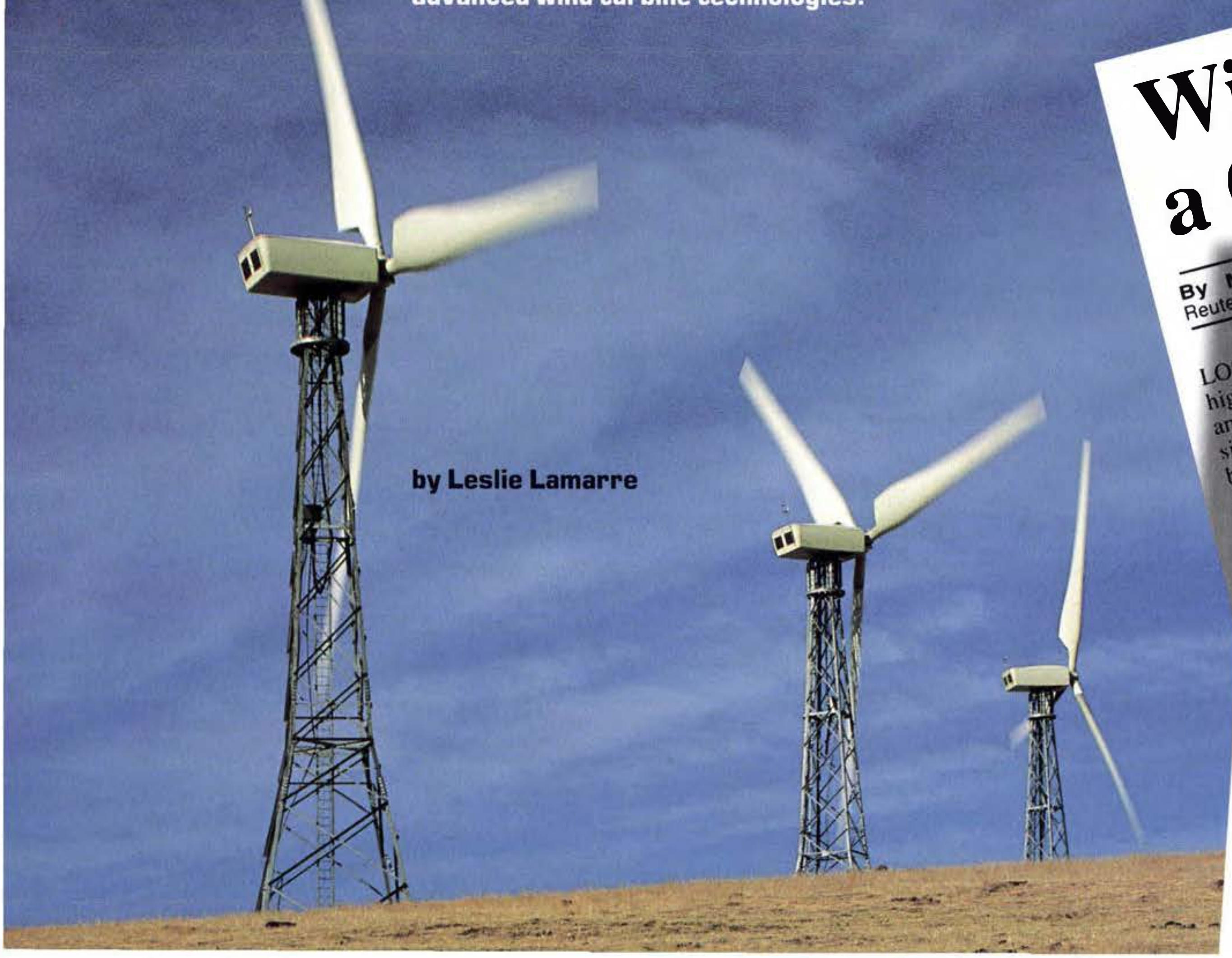
4 Wind

A GROWTH MARKET IN WIND POWER

THE STORY IN BRIEF Progress in wind turbine technology has spurred a revival of wind power projects across the United States. New confidence in the technology is reflected in the fact that electric utilities are opting to own the turbines directly rather than buying the power from independent wind farm developers. Recently implemented government and regulatory incentives are expected to further propel utility involvement. Wind power development is moving at an even more rapid pace in Europe, where government subsidies and incentives have progressed steadily over the years. Despite the advantage such subsidies have given to European companies, the dominant U.S. wind turbine manufacturer has produced a turbine that has successfully competed internationally. EPRI and the U.S. Department of Energy are collaborating on a new program to help accelerate the commercialization of even more advanced wind turbine technologies.



by Leslie Lamarre

ure of Wind Power Gets a Lift

ogy Advance Makes Cost More Competitive With Other Energy So

Thomas W. Lippman
shington Post Staff Writer

fornia, the dream of convert- s of the wind into electricity n a lot of hot air.

y federal tax credits, wind rief vogue in the early 1980s. apitalized manufacturers up "wind farms" of turbines

gies, left on the fringes of the nation's energy mix by the worldwide abundance of cheap oil.

But the wind energy story never ended in California, and reports from utilities in Iowa, Minnesota, New York and Vermont indicate that the book may be reopened elsewhere.

Now, as a result of a relatively simpl

efficiency of wind turbines e them competitive with other ergy.

The breakthrough was rep cent industry conference in a consortium consisting of tw utility industry's Electric Po Institute (EPRI) and the bigg manufacturer of win

FOR A TIME DURING THE 1980s, when wind turbines were going up on the blustery ridges of California at a rate of nearly 2000 per year, it appeared as if interest in wind power had reached its peak in the United States. But a recent gust of activity among utilities in different parts of the country has signaled the beginning of what many experts believe is a revival of wind power projects—with interest even more widespread than before, and with more intimate involvement from utilities.

Here are some examples of the attention utilities have given to new wind projects within the past year. Northern States Power Company has announced plans to bring a total of 100 MW of wind power on-line by 1997. Puget Sound Power & Light Company, in conjunction with three other utilities, plans to bring 50 MW of wind turbines on-line by 1996 in the Pacific Northwest's first large-scale wind generating project. The Bonneville Power Administration has put out for bid 50 MW of wind power it plans to bring on-line in 1996. Pacific Gas and Electric Company, a major player in earlier wind developments, has filed for a permit to install 7 MW of next-generation wind turbine prototypes between 1994 and 1996. Niagara Mohawk Power Corporation installed two turbines near Lake Ontario in November—the first utility-grade commercial turbines in the state of New York. And in the Midwest, the unregulated subsidiary of Iowa-Illinois Gas and Electric Company has formed a joint venture with the largest U.S. wind turbine manufacturer to market wind power to utilities in that region.

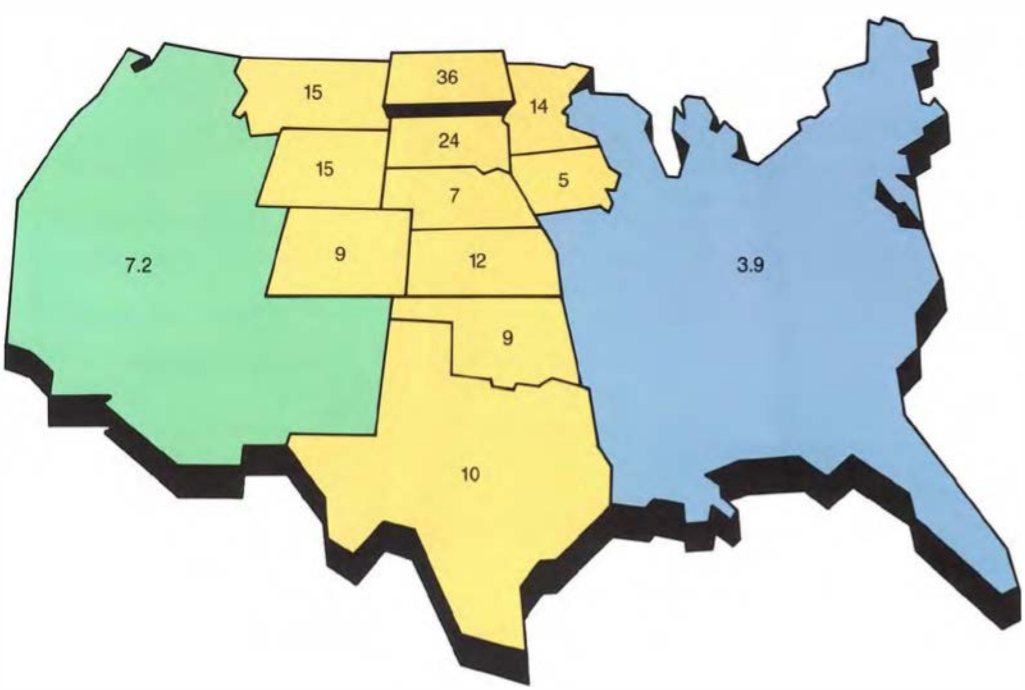
"In the early 1980s we witnessed a surge of utility involvement in wind power projects, but technological progress fell short of expectations," says Edgar DeMeo, who oversees EPRI's program for solar and wind power. "Now, 10 years later, technological progress has caught up with and even exceeded the early expectations, and as a result, the activity among utilities is expanding more rapidly than ever before." DeMeo notes that today's wind power development is geographically more widespread, too. "People used to think wind power was something that only Californians were into," he says. "But today, most of these projects are being undertaken in other parts of the country."

In a major departure from past practices, some of the utilities establishing new wind farms plan to own the wind turbines directly, rather than buying the power from a developer who owns the machines. DeMeo credits significant advances in technology for this increased interest in direct ownership. "The technology has reached a sufficient level of maturity for utilities to consider owning the turbines," he says. "It's not as risky as it was 10 years ago, before the industry settled on a preferred turbine size range and before we

The power of wind on Buffalo Ridge, Minnesota, prevents this boy from falling over. (Photo courtesy of John R. Dunlop)

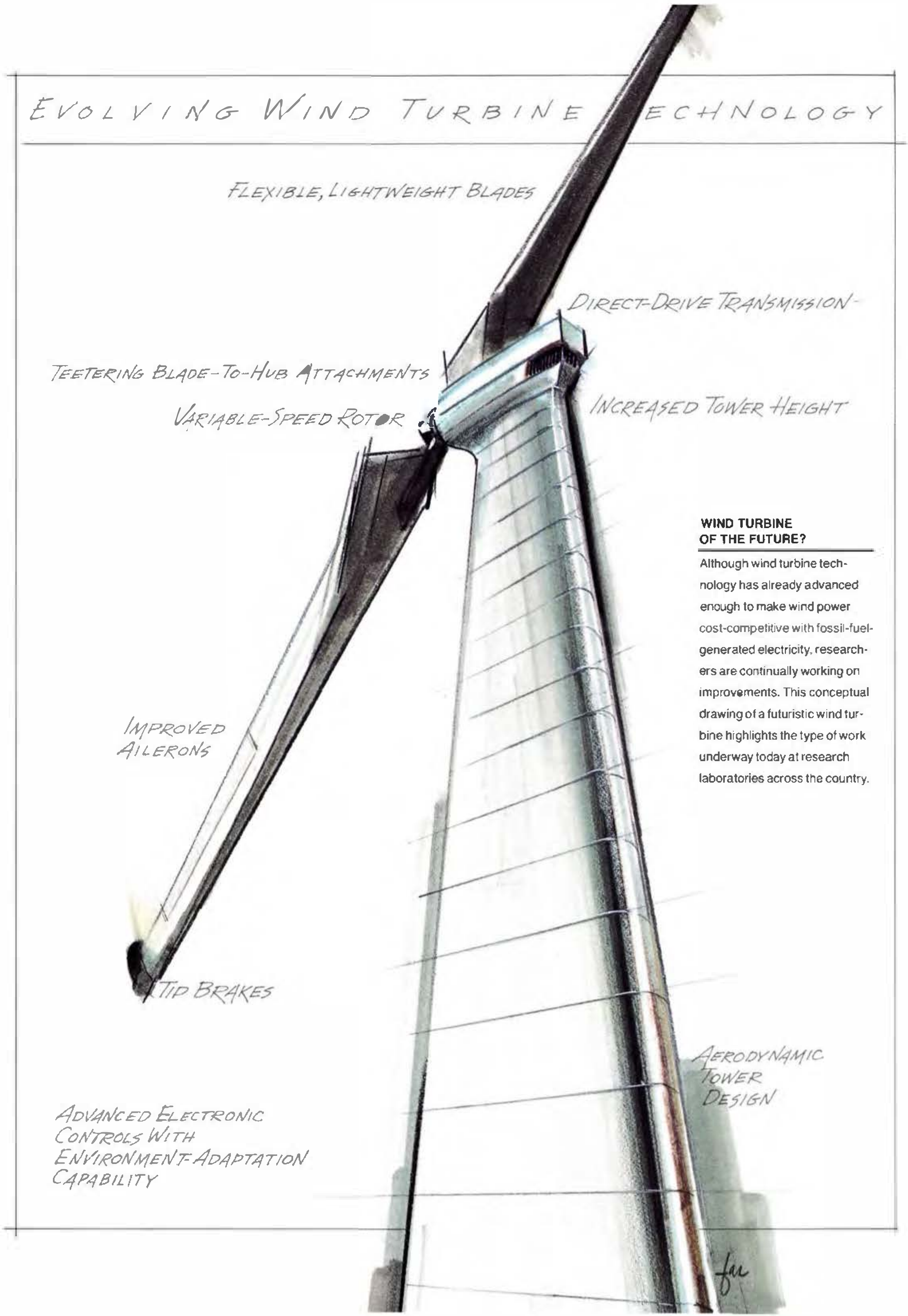
A lone turbine in the picturesque mountains of Vermont churns on despite its frigid environment.

Troops of wind turbines are as common as the California poppy on some Golden State hillsides.



WIND RESOURCES, COAST TO COAST

While ample wind resources are dispersed across the United States, the prime location for wind farm development is the central, Great Plains region. The numbers on this map represent the percentage of the 1990 electricity needs of the lower 48 states that could be met through wind power, given the wind resources available in the specified regions. For instance, North Dakota alone has enough wind resources to supply 36% of the electricity consumed by the contiguous 48 states in 1990. However, only a fraction of this wind power potential can be exploited economically.



WIND TURBINE OF THE FUTURE?

Although wind turbine technology has already advanced enough to make wind power cost-competitive with fossil-fuel-generated electricity, researchers are continually working on improvements. This conceptual drawing of a futuristic wind turbine highlights the type of work underway today at research laboratories across the country.

had the millions of hours of operating experience that have since offered critical feedback to improve turbine reliability."

Also, growing public concern about the environment has led to regulatory incentives that are encouraging wind projects. For example, the use of environmental externalities in utility resource planning is making renewable energy technologies like wind power more attractive. The confidence inspired by technological advances in wind turbines has prompted the implementation of other types of financial incentives, including a 1.5¢/kWh production incentive, part of the federal energy bill signed by President Bush in October. In addition, EPRI and the U.S. Department of Energy (DOE) have initiated a major program to accelerate the commercialization of wind turbines.

Today there are more than 16,000 wind turbines installed in this country—nearly all of them in California—with an aggregate power rating of nearly 1500 MW. These turbines generated some 2.7 billion kWh of electricity in 1991, enough energy to meet the residential needs of a city the size of San Francisco. But this country's abundance of high-wind regions (those with an average annual wind speed of 16 miles per hour or higher) offers the potential for thousands of additional wind projects. According to a study conducted for DOE by Battelle, Pacific Northwest Laboratory, if today's wind turbine technology took full advantage of these high-wind regions, it could generate 20% of the country's electricity. With the anticipated improvements in wind turbine technology, an even greater contribution could be achieved, says DeMeo.

Many of the best locations for wind projects lie outside California, with Montana, Wyoming, North Dakota, South Dakota, and Minnesota possessing a large chunk of the choice wind regions. The Northeast also claims considerable wind resources. In all, about 14 states possess wind energy potential that is equal to or greater than that of California.

To own or not to own?

Except for one wind power installation in Hawaii, all of the major utility-scale wind projects have been undertaken by independent developers who in turn sell the electricity to utilities. This is largely because in the past wind turbine technology was still in the research and development phase. Also, the financial incentives offered by the federal and state governments were available only to nonutility developers (i.e., independent power producers).

But much has changed since then. Perhaps most significantly, the major U.S. wind turbine manufacturer, U.S. Wind-

power, has developed a variable-speed turbine with support from members of the Variable-Speed Wind Turbine Development Alliance, established by EPRI and joined by Niagara Mohawk and Pacific Gas and Electric. The breakthrough turbine, the first prototype of which was field-tested in the spring of 1991, is expected to produce electricity for a record low cost of 5¢/kWh, given an average annual wind speed of 16 miles per hour. The new turbine is capable of producing electricity at varying rotor speeds. By contrast, virtually all other turbines on the market must operate at constant rpm to produce utility-grade (60-Hz ac) power. Because the extra torque generated by wind gusts must be absorbed by the drivetrains of constant-speed wind turbines, they require heavier designs than comparable variable-speed models.

While a few other variable-speed turbines have been developed in recent years, U.S. Windpower's model offers a much more advanced electronic system—including a sophisticated controller and converter—that does not send objectionable current distortions back onto the utility line. Because of its variable-speed capability, the new machine is rated at 350–450 kW. According to Kingsley E. Chatton, president of Kenetech/Windpower, the manufacturing arm of U.S. Windpower, the machine operates at wind velocities ranging from 9 to 60 miles per hour. Last summer U.S. Windpower undertook a major program, testing 22 of the new machines at the Altamont Pass in California. Data gathered from the tests are providing statistical information on the turbine operating and maintenance requirements and are helping to improve the technology's design. Any improvements will be incorporated into commercial units to be installed in the fall of 1993.

U.S. Windpower's achievement not only has pushed utility turbines beyond the R&D level, it has bumped them into a cost-effective price range for utilities. And with the availability of many turbines on the market now routinely running at or above 95% (compared with 50–60% in the early 1980s), there are a number of advantages to utilities' owning the machines. To start with, points out Earl Davis, EPRI's manager of wind power integration, utility ownership is cheaper because utilities, which have access to much more capital, can get lower financing rates than the smaller, independent developers and entrepreneurs, who are viewed as a riskier investment. In addition, because more middlemen are involved in financing the projects of independent developers, their up-front financing costs are greater and add to the total installed cost. In the end, the cost of energy from a wind power plant owned by an independent power producer could be 30–40% greater than that of energy from the same plant if owned by a utility.

Northern States Power, which in August announced its plans to install 100 MW of wind generation, plans to own the first 25 MW. The remaining 75 MW will be put out to bid and may be owned by NSP or by an independent power producer, says Glynis Hinschberger, the utility's manager of energy resource planning. "The reason we want to own the initial block of turbines is to get some operating experience for ourselves," Hinschberger says. "We have experience with other generation

Some Advice on Wind Farm

Because only a handful of electric utilities in the country have actually owned their own wind turbines, there is a limited amount of documented experience available for utilities to take advantage of. Earl Davis, EPRI's manager of wind power integration, is working to fill this knowledge gap, in part by developing a primer on wind farm development. This handbook is scheduled to be published next year.

"Certainly utilities have a number of challenging issues to deal with if they want to own their own turbines," says Davis. "But there are a number of benefits as well, including the ability to have greater control of the turbine operations and of the way this energy resource is going to be integrated with their other generation sources."

Davis recommends that utilities considering direct ownership of wind machines first thoroughly measure their wind resources to determine what wind conditions prevail in the areas of specific interest to them. Next, they should analyze available turbine technology to find out which machines are most appropriate for their weather conditions. Before making any commitment to install the technology, utilities should examine the potential for snow, ice, heavy rainfall, tornadoes, and other extreme weather conditions that may affect the maintenance and operation of the turbines. Also important is investigating whether any endangered or sensitive species inhabit potential wind farm sites. According to Davis, utilities should address existing land use as well, taking into account whether a given site has been cultivated and whether there are houses nearby.

Land ownership is another issue to consider. There are several options. A utility might buy one large block of land to accommodate several clusters of wind turbines, or it might purchase only the specific ridges on which the turbines would be located. Similarly, the utility could lease the entire parcel or just those sections needed for tapping the wind resources. A third option is leasing the "wind rights" to the land, which would allow the present owner of the land to continue using it while simultaneously offering the utility the rights to install wind turbines, access roads, transmission lines, and other equipment required to operate and maintain a wind farm.

During the preliminary, feasibility phase of a wind farm project, the utility should lay out a plan to collect the electricity produced by the turbines and transmit it to the utility grid, says Davis. In addition to the technical considerations, the utility must look at the staffing requirements for the wind plant, determining where and how it will be operated and how to monitor its performance. Because many wind plants are located in remote areas, often a local office must be established. Finally, the utility should establish a performance verification program to determine the percentage of the available energy that is actually captured and to identify ways to improve the energy production.

Workers erect two wind turbines near Lake Ontario for Niagara Mohawk Power Corp.

Development

Davis stresses that utilities need to get professional assistance from experts they may not have in-house, such as wind energy meteorologists. "Wind energy meteorology is a new specialty," Davis says. "A very limited number of people have had the opportunity for experience in this area." Al Manning, former president of Hawaiian Electric Renewable Systems (HERS), agrees, noting that boundary-layer meteorologists, who specialize in the interactions between terrain and the air masses above it, should be involved in the early planning phases. HERS is a subsidiary of Hawaiian Electric Industries, the only utility in the country with experience in owning substantial wind-powered generation capacity.

Since the mid-1980s, Hawaiian Electric Industries has owned and operated over 12 MW of wind capacity. Acknowledging an announcement in October of this year that HERS plans to shut down its major wind installation, consisting of 16 wind turbines on Oahu, because of chronic mechanical problems and poor financial performance, Manning noted the significant differences between these projects and those being pursued by utilities today. One of the turbines to be shut down is the largest horizontal-axis wind turbine in the world, a 3200-kW machine installed in 1987. The remaining 15 are 600-kW units. "These machines were the only ones of their kind in the world," Manning says. "When parts were needed for these turbines, we frequently had to have them made."

Having replacement parts custom made meant that the machines were out of commission for relatively long periods. In addition, the turbines were much more expensive to start with—about four to five times the cost of turbines on the market today, Manning says. The crane required to erect the biggest machine was larger than anything available from the construction industry in Hawaii; it had to be shipped from the U.S. mainland and returned after the installation was completed. "These turbines were created when the industry was still experimenting with turbine size," says Manning. "Today's turbines offer a more realistic capacity range."

Two types of forums are available to utilities that are interested in learning more about wind power technology and logistics. The Utility Wind Interest Group, which receives support from EPRI and the U.S. Department of Energy, helps keep its members informed on the status of wind turbine technology and produces brochures on the use and development of wind power. Currently, 12 utilities from across the country belong to the interest group. Also helpful are the Advisory Councils for Wind Energy, through which utilities that are seriously pursuing wind power can exchange experiences and information on issues—such as system integration, wind resource valuation, and land use—that must be addressed throughout the wind farm development process. At present there are two of these advisory councils, one for the Northwest and one for the Southwest. Davis is exploring the possibility of establishing similar councils for the Midwest and Northeast regions of the country.

"One message we are trying to get across is that utilities do not have to repeat the mistakes others have already made. We have learned from past experience and can help our members through the process. They do not have to do this on their own." Davis encourages utilities who need assistance to contact him at (415) 855-2256. □

technologies, and we'd like to get more with this one. If this is a technology we're going to be relying on in the future, we'd like to get some idea of how it works."

Melanie Granfors, spokeswoman for Puget Sound Power & Light, says Puget and the other utilities involved in the Pacific Northwest project (Idaho Power, Portland General Electric, and PacifiCorp) chose to own the turbines simply "because it was the least-cost option." Explains Granfors, "It was less expensive to own

the turbines than to purchase power from them." Benton County Public Utility District has been invited to join the project, but at press time the utility had not responded with a final answer. While details of the agreement with the turbine manufacturer, U.S. Windpower, are still under negotiation, the utilities plan to contract with the company to operate and maintain the turbines for a certain period early in the project. The plan is for utility staff members to gain experience with operation and maintenance before taking over these responsibilities.

Regardless of whether utilities interested in wind power own their turbines directly or purchase power from developers, they face some major challenges. One of these is the issue of land use. Unlike the early wind power developers in California, who had access to large tracts of land—typically measuring 2–10 square miles and owned by a single farmer—the Midwest utilities are dealing with smaller tracts, very similar to those in Europe, which have been divided into several sections (typically four owners for every square mile of farmland). Whereas the California land is generally used for dry farming and cattle grazing, the Midwest sites have been planted with crops, a use that can pose some obstacles to the installation of turbines and access roads. Davis views the European utilities' experience as a valuable complement to U.S. experience and is working with EPRI members to make the best use of knowledge gleaned from the overseas industry.

Incentives: the ups and downs

Substantial tax credits at both the state and federal levels played a crucial role in California in offsetting what was viewed as the considerable financial and technical risk of early utility-scale wind turbine development. While these credits were not available to utilities, independent developers were eligible to receive them, and the incentive did much to encourage the installation of wind turbines. Turbines began sprouting up in the late 1970s, primarily in California but also in other parts of the country. Many of these early machines were prototypes, and testing and engineering were typically performed in the field. The resulting high failure rate tarnished the reputation of wind power. Nevertheless, buoyed by support from the federal and state governments, and encouraged by tentative interest from some utilities who viewed wind as a future opportunity, the initiation of wind projects continued.

In 1985 the federal tax credits expired, followed a year later by California's tax credits. However, significant improvements in turbine technology, together with the continuation of another type of incentive in California, known as Standard Offer 4 contracts, made possible the financing and installation of thousands more turbines, even in the face of falling fossil fuel prices. Standard Offer 4 contracts essentially guaranteed a minimum price for wind energy over a period of years, enabling wind farm developers to obtain the financing they needed. As more turbines went up, much-needed operating experience was gained, system reliability improved, and the cost of installed projects decreased dramatically, from more than $2000/kW in the early 1980s to about half that by the end of the decade. This brought the cost of wind energy down from 25–30¢/kWh to 7–9¢/kWh, assuming an average annual wind speed of 16 miles per hour. Starting in the mid-1980s, no further Standard Offer 4 contracts were issued. As a result, the installation rate slowed considerably, causing some observers to wonder whether the golden age of wind power had already come and gone.

Technological progress is the engine driving today's activity in wind power.

But new types of incentives are beginning to come to life, and they are expected to add fuel to the wind power movement. Largely reflecting a revival of interest in and commitment to renewable energy technologies, the incentives are propelled primarily by environmental concerns, but also by a desire for national energy stability—an interest that was reinforced during the recent war in the Persian Gulf. Among other factors that are making wind power attractive for more utilities is the need to use environmental externalities in developing plans for future power generation.

Environmental externalities are impacts —both positive and negative—that are not reflected in the market prices of generation options. For instance, releases of carbon dioxide and nitrogen oxides are negative externalities associated with burning coal. Such externalities might be added to the cost of using coal, or instead a credit might be given to renewable energy resources, such as wind power, for *not* generating such emissions. As a result, utilities, which typically use a least-cost method for selecting future generation, will take these factors into account, since they are reflected in the bottom-line figure for each option. New York, Wisconsin, Vermont, and Oregon are just some of the states whose utilities are including externalities in the generation planning process. Other states, like Minnesota, have adopted different incentives, including sales and property tax exemptions.

Meanwhile, the federal government has renewed its own incentives. In October President Bush signed an energy bill that includes a 1.5¢/kWh production incentive. For investor-owned utilities this incentive comes in the form of a tax credit. For tax-exempt utilities (including municipals and cooperatives), it comes in the form of a payment, dependent on the annual appropriations of the U.S. Congress. The incentive will go to the owners of wind plants that are brought on-line between January 1, 1994, and June 30, 1999. The credit will be available for the first 10 years of a wind plant's operation and will be adjusted annually for inflation. As Davis points out, this production incentive may further encourage utilities to purchase their own turbines, since they are the ones likely to benefit most. For instance, a 1.5¢/kWh credit on a 40-MW project, which would typically produce 100,000,000 kWh per year, would result in tax savings of $1.5 million. Private developers would be unlikely to reap the full benefits of such a tax break, since their tax bills are typically well under $1 million, which is less than the allowable tax credit. An investor-owned utility's tax bill, on the other hand, may well amount to several million dollars, so the tax credit is a good financial incentive for utilities—a benefit that also flows through to the customer by reducing energy costs.

Winds of Europe

The use of incentives in European countries has proceeded at a much more even pace, illustrating a steadily increasing commitment to wind power. And while the world's attention in the 1980s was fixed on the hills of California, it appears that Europe will soon steal the show and far surpass the United States in turbine installations. According to Michael Marvin, director of government and public affairs for the American Wind Energy Association, "By the end of the decade, unless current trends change, Europe will dominate world production of wind-generated electricity."

Government policies are the driving force behind Europe's increased commitment to wind power. The ministries of energy, environment, and research and industrial development in various countries have established long-term energy and environmental policy plans. Combined, the European programs call for the installation of at least 4000 MW of wind capacity by the year 2000. The United States, meanwhile, has set no national goals for the implementation of wind technology. Among the European countries expected to be most active in wind power this decade are England, Denmark, Germany, and the Netherlands. Significant activity will also be occurring in Alberta, Canada.

The OEM Development Corporation, which compiled a soon-to-be-published EPRI report (TR-101391) on wind technology in Europe, points out that the European commitment to wind projects in the 1990s more than doubles the 1600 MW of wind capacity that exists in the United States. "While some of these goals may not have the force of law, it is clear that European governments are serious about wind and are attempting to give this and other renewables every chance to be implemented on a significant scale," according to Jamie Chapman, author of the OEM report. The European Wind Energy Association projects the installation of 11,500 MW of wind capacity by 2005, 25,000 MW by 2010, and 100,000 MW by 2030.

What's prompting European countries to leap so confidently onto the wind bandwagon? They are reacting to factors similar to those propelling the U.S. market for wind power: uncertain oil prices, mistrust of nuclear power (a growing unease that was precipitated by the Chernobyl accident), and increasing damage to the environment from the use of fossil fuels. DeMeo of EPRI points out that environmental concerns clearly dominate. "A number of European countries have come to the conclusion that they need to do something not only to reduce acid rain but to minimize greenhouse gases as well. Wind is a favorite option for them because most of the European countries have good wind resources and because of the status of the technology."

DeMeo sums up the difference between the European and the U.S. perspectives today as follows: "In this country, utilities are trying to decide whether they should use wind power and under what conditions it is going to make sense. In the European countries, the decision to use wind

power has already been made by the government and the people, so the question the utilities there face is *how* they are going to use it, not *whether* they are going to use it."

One strength of the European movement is that it represents many sectors of society, including government bodies, utilities, academic institutions, and manufacturers. The Commission of the European Communities and the national government programs are the major forces supporting advances in the technology—facilitating and even mandating the involvement of utilities, demonstrating new turbines, and stimulating the market. Of great significance with respect to utility participation, European utilities—unlike their counterparts in the United States during the 1980s—have been allowed to receive tax credits and other financial incentives.

The European government programs have also been of major benefit to European turbine manufacturers. In fact, so strong is governmental support that subsidies have led to the development of machines far more expensive than those produced in the United States. While U.S.-manufactured turbines now cost less than $1000/kW installed, European machines typically cost 50% more and weigh about twice as much. Although European turbines may not be cost-competitive with American-made models, some of them offer extremely attractive features, points out DeMeo. In particular, he says, several machines produced by Danish manufacturers offer high reliability, and a German manufacturer has produced a variable-speed turbine similar to U.S. Windpower's. The heavy subsidies in Europe—inspired by governmental desire to foster domestic industry—certainly make the European market hard to break into. But U.S. Windpower did just that last summer, winning a bid to sell 25 MW of wind power to a utility in Holland.

Competition on the rise

While U.S. Windpower clearly dominates the wind power market in the United States, other domestic manufacturers are producing advanced turbines that are expected to become competitive within the next few years. In fact, the U.S. Department of Energy, through its Advanced Wind Turbine Program, is sponsoring the development of five turbines in an effort to provide wind power for 5¢/kWh, assuming sites with an average annual wind speed of 13 miles per hour, by 1995.

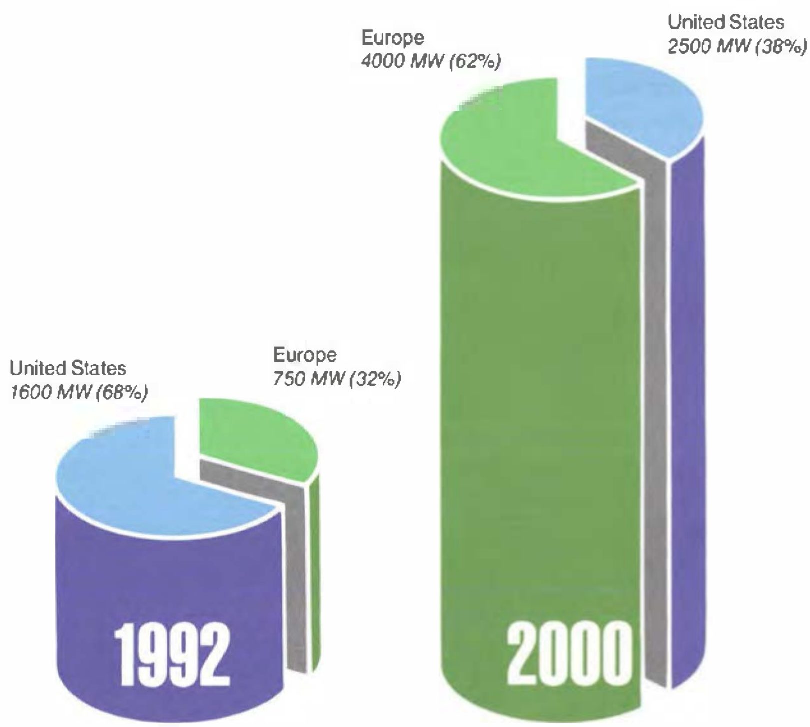
Among the most promising machines in the DOE program is R. Lynette & Associates' two-bladed turbine, rated at a capacity of 275 kW. A very lightweight machine, it is expected to weigh about half as much per kilowatt as most of the three-bladed commercial turbines available today. Because the machine is so light, it should be inexpensive to build. It employs advanced blades, designed by DOE's National Renewable Energy Laboratory, that increase energy capture. The control system takes advantage of the aerodynamic nature of the blades, so they automatically stall in high wind to ensure that the maximum power rating is not exceeded. This machine is to be available for initial commercial delivery in 1994.

Another promising machine selected for funding through the DOE program is Northern Power Systems' turbine, which

THE WORLD ACCORDING TO WIND POWER

Wind farm at the outer harbor of Zeebrugge, Belgium

Currently the United States has the bulk of the world's wind power capacity, accounting for 68% of all installed capacity in 1992. But experts project that by the end of the decade, Europe will be the dominant force in wind power, accounting for 62% of the total installed wind power capacity worldwide. Aggressive government programs that set national goals for wind turbine installation and subsidize wind power projects are the driving force behind Europe's increased commitment to wind power. Other countries, such as India, have also installed wind turbines, but their activity is negligible in comparison with U.S. and European involvement.



is expected to provide 250 kW of capacity. Also a two-bladed, lightweight design, this turbine employs aileron controls and a teetering rotor, which allows the blades to rock back and forth to adapt to uneven wind pressures. The ailerons, similar to those on the wings of an airplane, represent a major advance in wind turbine technology. The adjustable flaps can regulate how fast the rotor spins and are used to control the starting and stopping of the machine. This turbine is expected to be commercially available in 1995.

DOE's Advanced Wind Turbine Program, established in 1990, is a major part of a larger federal wind program and is intended to bolster the U.S. industry. "We believe a strong manufacturing base with multiple players will lead toward a healthy industry," says Ron Loose, director of the federal Wind Energy Program. "We feel that for wind to be accepted by utilities as a domestic energy option, we must have a diverse supply of quality domestic turbines."

To further advance the development of emerging turbine technologies, EPRI and DOE have established the Utility Wind Turbine Performance Verification Program. Created through a memorandum of understanding signed by the two organizations in September, the program aims to accelerate wind power commercialization and facilitate utility involvement. The program's long-term objective is to ensure the commercialization, by the year 2003, of field-verified, state-of-the-art, utility-grade wind power systems capable of delivering electricity for 4¢/kWh (in 1992 dollars), given 13-mile-per-hour winds. This represents a more than 20% decrease in the cost of energy produced by today's state-of-the-art technology.

Arrangements established through the memorandum of understanding call for DOE—as is consistent with its Advanced Wind Turbine Program—to fund the development and initial testing of advanced wind turbines. EPRI and the participating utilities will provide the testing ground for the turbines. Four utilities are each expected to install and operate 20 or more commercial prototype turbines, including at least 10 of each turbine type. EPRI is currently seeking members from different parts of the country to act as host utilities for the program and is encouraging interested utilities to get others involved as cosponsors.

The machines will be deployed and evaluated for three years, enough time to allow a thorough assessment of their energy cost and suitability for large-scale application. The turbine testing will get under way in 1994. As DeMeo points out, the data gathered will provide valuable experience and feedback on the turbines' operating performance and maintenance requirements—the kind of information required before a major installation. The program's capital expenses are expected to run about $10 million per host utility site, with half to be provided by the host and the remainder by EPRI, partner utilities, and DOE. EPRI's portion includes an estimated $1.5 million for basic program support, excluding tailored collaboration funds that are available to member utilities.

Although DOE is sponsoring the testing of U.S. machinery only, EPRI funds are available for both foreign and U.S. turbines. The decision on which machines to employ is left to the host utilities. Currently available machines are eligible for the program, but the major emphasis will be on emerging turbines. Nevertheless, as DeMeo points out, most of the existing turbines have been field-tested only in California and Hawaii. "When you get into the vast expanses of Wyoming with 10 feet of snow on the ground, wind turbine performance is a whole different story."

"The early commercialization of a product is critical to its success," says Davis, noting that the program will help manufacturers receive early orders for commercial turbines and thus help to drive down the cost of the machinery. "An equally important objective," he says, "is to allow pioneering utilities to gain experience in operating turbines without having to assume the entire risk associated with a new power generation technology."

Marvin of the American Wind Energy Association believes the EPRI-DOE program will help pack much-needed power

into the U.S. turbine-manufacturing muscle. According to him, "U.S. Windpower's breakthrough was only the beginning. Now we'll begin to see some more competition emerge. I think the mid-nineties are going to be a tremendously exciting time for the wind power industry. The best in wind is yet to come." ■

Further reading

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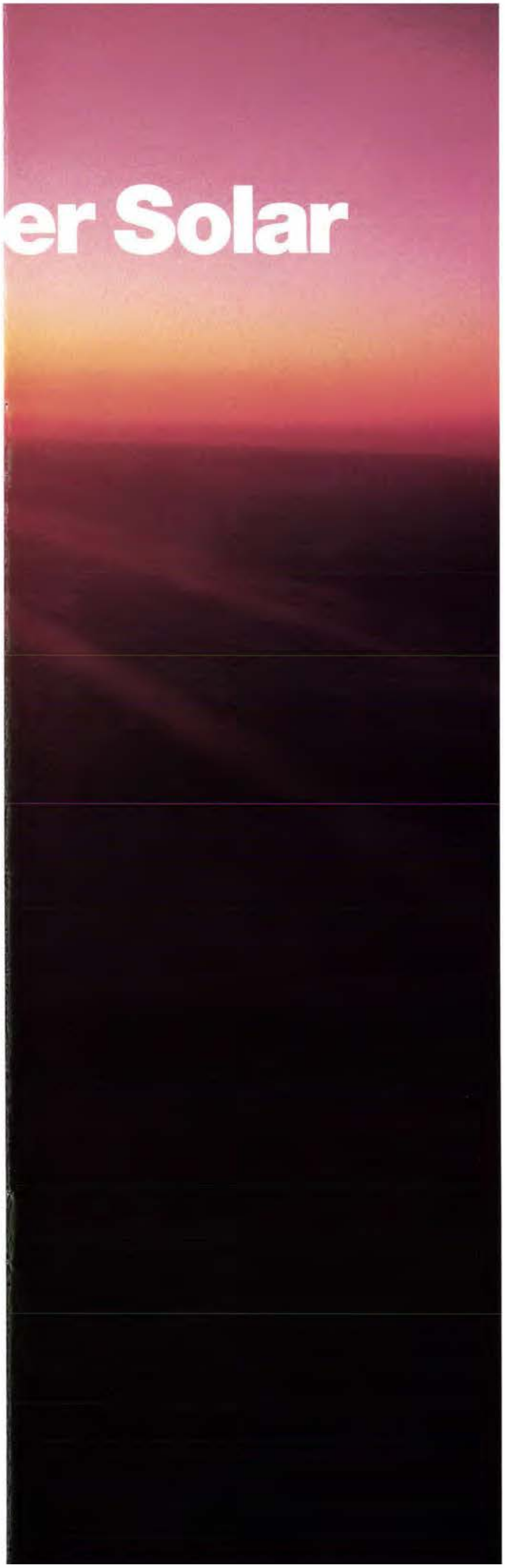
High Hopes for High-Pow

THE STORY IN BRIEF In the mid-1980s, researchers at Stanford University surprised the solar research community with the highest solar cell efficiencies that had yet been seen in the laboratory. But tough challenges stood in the way of making the cells both durable and affordable. Many of the hurdles have now been overcome, and two startup companies are pursuing commercial solar generating systems based on the technology developed through EPRI and utility support. Still, experts say interim markets may be needed on the path to utility-scale power generation to ensure the technology's eventual commercial competitiveness.



by Taylor Moore

HIGH-CONCENTRATION SOLAR PHOTOVOLTAIC CELLS ARE NEARING COMMERCIALIZATION, building on the success of EPRI-sponsored work at Stanford University in the mid-1980s that achieved a world-record sunlight-to-electricity conversion efficiency of over 25%. Developers have since made major progress in clearing the technical and manufacturing hurdles that separated laboratory cell prototypes from durable, field-deployable power-generating systems. As a result, two startup firms are planning to become commercial manufacturers of sun-tracking systems based on the technology. Research managers at the Institute say that within the next few years, such systems will likely meet the cost and performance targets set by EPRI over a decade ago for practical and economically competitive utility-scale power generation.

Full-size, prototype modular arrays featuring two different design approaches to using the concentrator technology under EPRI license are planned for installation next year. The arrays are to be installed at the PVUSA (Photovoltaics for Utility-Scale Applications) solar demonstration site located in Davis, California, and operated by Pacific Gas and Electric Company (PG&E). One of the companies pursuing the technology—AMONIX, Inc.—is leading the commercialization of a new, low-cost integrated array design for which a patent was issued to EPRI earlier this year. EPRI plans to begin construction of a prototype integrated array at Georgia Power Company's Shenandoah solar demonstration site late this year, and AMONIX plans to supply another integrated array to the PVUSA project.

In contrast to simpler—but less efficient—large-area, flat-plate solar modules (which typically operate at a fixed tilt facing south and convert some indirect as well as direct sunlight into electricity), concentrating systems use Fresnel lenses, parabolic mirrors, or heliostats along with sensors and motors to actively track and focus sunlight onto small cell areas. Concentrating systems generate up to 500 times more current per unit of cell area than flat-plate systems do. Some of the area that would be taken up by high-cost cells in flat-plate systems is devoted to lower-cost lenses or mirrors in the concentrator technology.

Because concentrating systems are more efficient, they require relatively few high-power arrays to equal the output of a large field of flat-plate systems. High-concentration photovoltaics (HCPV) has long been a leading candidate among solar technologies to provide an economically competitive generation option that could make a significant contribution to the bulk power supply.

The story of EPRI's effort in HCPV is one of a sustained commitment to a simple vision, according to Jim Birk, director of the Storage & Renewables Department in the Generation & Storage Division. "The vision is that the technology, with its small, highly efficient cells, has the intrinsic characteristics to achieve economic viability to complement its inherent environmental attractiveness.

"EPRI's commitment, which is probably unmatched in length of time by any organization involved with photovoltaics outside of Japan, has allowed remarkable progress, albeit not always at a steady or predictable rate," adds Birk. "Since the inception of the HCPV program, the key driving factors have changed from the cost and availability of fossil fuels to a growing recognition that renewables are becoming cost-competitive supply expansion options that are relatively free from environmental concerns. Also changed are the markets, possible ownership of generating systems in the future, the political and regulatory environments, and federal support and emphasis. HCPV is one of those technologies that's been driven by the simple concept that a clean, cost-effective, sustainable resource will find major application in energy supply regardless of how the utility industry changes."

Complementing EPRI's commitment, five cosponsoring utilities—Arizona Public Service, Georgia Power, the Los Angeles Department of Water & Power, PG&E, and Southern California Edison—have contributed to the effort beyond their EPRI dues. "These utilities have played a key advisory and funding role since the middle of the 1980s," says Edgar DeMeo, EPRI's program manager for solar power. "Most have stayed with the program through the inevitable ups and downs. And collectively they provide a regionally diverse test-bed for the technology as it evolves."

A solar cell on a chip

EPRI's solar concentrator cell technology grew from research that began in 1976 at Stanford University. Led by Richard Swanson of the Department of Electrical Engineering, the researchers used extensive computer modeling of the fundamental physics of a silicon photovoltaic device to eventually design and make a cell about 1 cm^2 in area and only 75–100 μm thick. The new design maximized the creation of pairs of charge carriers (electrons and holes) by incoming light photons and minimized their recombination in the material in order to produce the greatest flow of current possible.

Originally designed for 500× sunlight concentration, the cell had operating temperature limits and related cooling requirements that resulted in a small active area. But the cell's size and microelectronic design made it amenable to volume manufacturing by the same techniques used to make dozens of integrated-circuit chips on a single silicon wafer 3 to 6 inches in diameter. The larger the wafer, the lower the production cost of each device made on it.

The Stanford point-contact cell was a back-contact device in which thousands of alternating, microscopic contact points on the bottom surface collected the current generated from light that entered through the top surface. Antireflective coatings and texturing on the top and a reflective bottom layer helped trap light inside the bulk silicon to generate maximum current. A top layer of very pure silicon dioxide served to passivate the surface of the bulk silicon and prevent electron-hole recombination.

By the mid-1980s, Swanson and his associates were producing limited numbers of cells in the laboratory with PV conversion efficiencies of just over 28%—efficiencies that were confirmed by the U.S. Department of Energy's Sandia National Laboratories PV measurement facility. Higher efficiencies have since been reported by other developers for more exotic and costly gallium arsenide–based cells. (Originally designed for space power applications, even such advanced technologies could eventually find their way into terrestrial power application.) But the EPRI-Stanford efficiencies, which are within a few percentage points of the theoretical limit for a silicon-only device, still stand as a world record.

A semiconductor device maker in California's Silicon Valley—Acrian, Inc.—was contracted by EPRI to demonstrate the feasibility of manufacturing the point-contact cell in a pilot production facility. Concurrently with work on the cell, in the early 1980s EPRI had begun a supporting effort led by Black & Veatch on the design

EPRI HCPV TECHNOLOGY DEVELOPMENT: FROM LABORATORY TO MARKET ENTRY

EPRI's high-concentration photovoltaic technology originated in work proposed by Stanford University in 1976. Related hardware development for prototype modules and arrays was initiated in parallel in the early 1980s through the U.S. Department of Energy's photovoltaics program. By the mid-1980s, Stanford researchers had achieved a world-record sunlight-to-electricity peak silicon cell conversion efficiency of 28% at 100 suns illumination. But concurrently, instability and performance degradation began to be observed in early production cells. A refocusing of the research in the late 1980s produced technical solutions that have resulted in cell designs that are stable and 25% efficient. Two companies are now pursuing commercialization of the technology under EPRI license, using different cell and system design approaches.

and development of the surrounding cell package, the Fresnel-lens-topped module housing, and the array structure. Over the years, several prototypes of module and array designs — forerunners of the present integrated array — have been field-tested at utility demonstration sites in Arizona, California, and Georgia.

The early module design called for mounting individual cells on electrode assemblies that were then bonded to copper contacts and fitted with secondary optical elements to help the Fresnel lenses concentrate light onto the cells. Forty-eight cells, each fitted with copper heat spreaders on the underside, were mounted in the bottom of a deep-drawn aluminized steel pan. The module was then covered by two 24-cell, molded-acrylic Fresnel lens parquets to become the building block for 60-module, 18-kW arrays mounted on motorized pedestals. It would take 560 such arrays spaced over 60 acres to total 10 MW of peak-rated power, or 5600 arrays spread over 600 acres to make 100 MW.

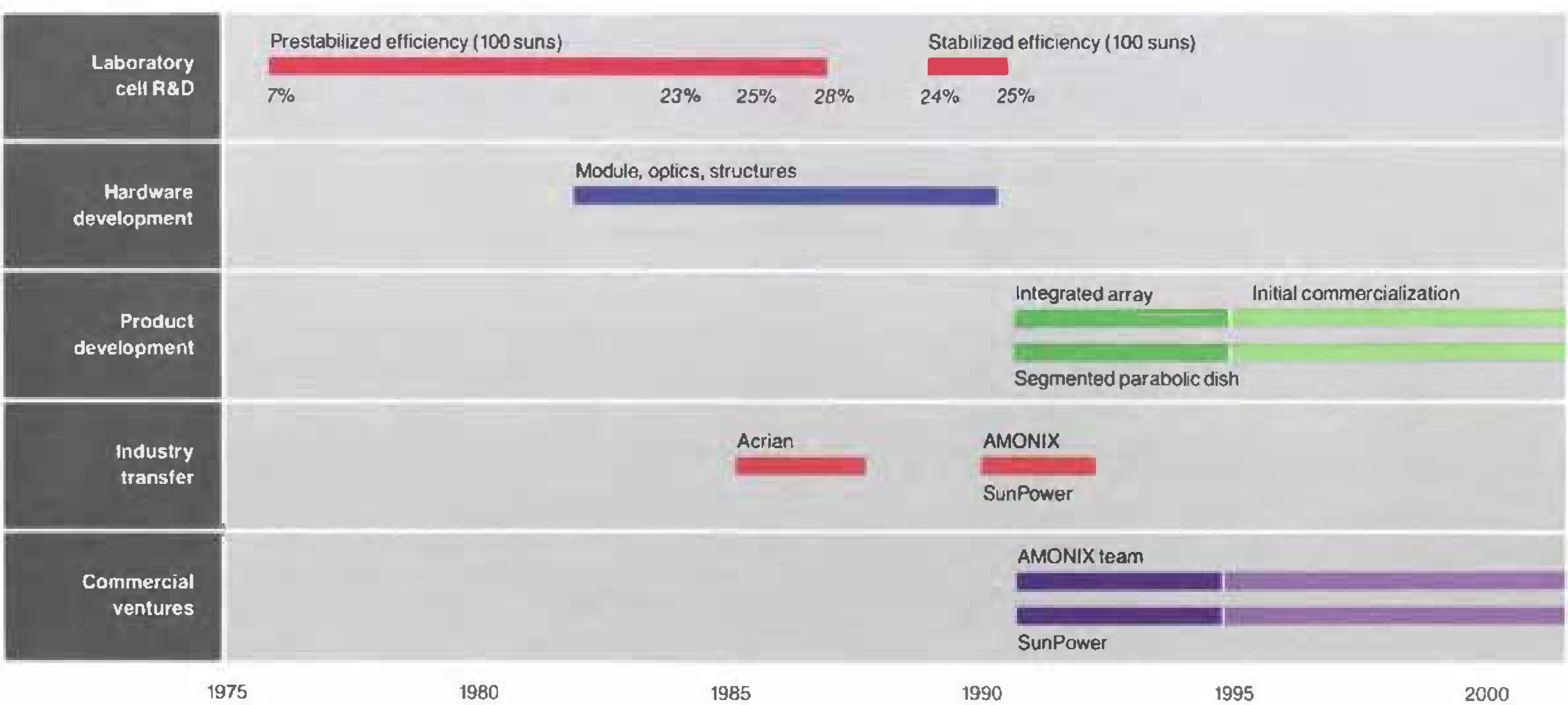
As work progressed through the 1980s, "we gained a lot of experience and knowledge about the kinds of problems that can be encountered when trying to produce these cells in a high-volume manufacturing environment," says Frank Dostalek, an EPRI project manager. Yet the feasibility of large-scale manufacturing of concentrator cells using the standard semiconductor processing techniques of photolithography, diffusion, and metallization was clearly demonstrated.

What was not anticipated, and what forced a major refocusing of the technology development effort in the late 1980s, was the disturbing observation of performance instability and degradation in early production cells that had undergone extended illumination testing. Some cells lost as much as 15–20% of their output power within the first few days of exposure to sunlight — and as much as 40% within a few months. For a while, the outlook for the EPRI-Stanford high-concentration solar cell seemed dark.

The stability problem sent Stanford researchers back to the drawing board and their three-dimensional model of cell physics to figure out what was going on. EPRI also convened a number of meetings of experts, including a panel of scientific advisors, for input and insight. It was a full year after the instability was first observed before researchers worked out a theoretical understanding of the performance degradation and successfully implemented a technical solution.

Early into the problem, experts had noted similarities between the efficiency loss in the concentrator cell — fabricated from high-purity, low-defect crystalline silicon — and the loss of power output with prolonged exposure to light in thin-film solar modules fabricated from noncrystalline, amorphous silicon. (Other groups in the photovoltaics community and EPRI's solar R&D program were already addressing the latter problem.) But as theories about the concentrator cell's instability evolved, it became clear that the phenomena in the two cell technologies were distinct. The so-called Staebler-Wronski performance loss experienced by amorphous silicon is now understood to be caused by light-induced bonding defects created throughout the material. In contrast, the degradation in the concentrator cell appeared to occur as a result of something going on only at the interface between the cell's passivation layer of silicon dioxide and the bulk silicon.

The passivation layer was added on the



top surface of the cell because it was believed to tie up dangling covalent bonds of atoms at the edge of the bulk silicon that would otherwise form sites for electron-hole recombination and thus limit current collection. When the cell was annealed at a high temperature, hydrogen was added to the passivation layer to tie up more dangling bonds at the interface; unfortunately, the hydrogen bonds are weak and easily broken.

According to the theory developed by the Stanford team, photons of the ultraviolet (UV) component of solar radiation entering the silicon cell carry enough energy to create energized, or hot, electrons that are injected from the bulk silicon into the silicon dioxide. The injection process breaks many of the weak hydrogen bonds at the silicon–silicon dioxide interface. Electron-hole recombination then increases as the surface loses passivation, and conversion efficiency drops.

In work funded by EPRI, the Stanford researchers developed a twofold solution to the stability problem. First, they improved the passivation layer, producing a clean, dry layer that reduces mechanical stress at the interface and thereby limits defects and related recombination. Second, they diffused a shallow layer of phosphorus (*n*-type) dopant into the cell surface. The shallow-doped layer creates an electric field that repels positive charge carriers (holes) away from the passivation interface and thereby prevents further recombination.

Although the diffusion of additional dopant makes for a stable device, it unfortunately robs the cell of 2 to 4 percentage points in efficiency. Improved stabilization techniques now under development are expected to restore this lost efficiency.

"The stability problem is under control. Two solutions have been implemented and others may exist," says Frank Goodman, another EPRI project manager involved with the concentrator cell effort. "We've had approximately 200 cells under test for an extended period, including three modules for over two years and a fourth module for a year. No efficiency degradation has been observed. The earlier cells would start to degrade right away."

Onward and upward

Both of the startup firms to which EPRI has provided funding and management support to pursue commercialization of the solar concentrator technology—AMONIX and SunPower, Inc.—have implemented their own solutions to the stability problem, and both have developed their own design concepts for incorporating the high-efficiency cells in high-efficiency systems. EPRI has awarded each firm its first large production order for 2000 cells.

SunPower says it is able to consistently make 21%-efficient, stable cells by using shallow dopant diffusion but hopes soon to eliminate it and reclaim the lost efficiency. Richard Swanson, the founder, vice president, and director of technology for the Sunnyvale, California, company, notes that SunPower is exploring recent progress in the related area of complementary metal oxide semiconductor, or CMOS, technology with the hope of developing an improved, stable oxide layer that is resistant to damage by hot electrons.

"Since the microelectronics industry has a similar problem, we have a hunch we can borrow from their practice and get a rugged, stable oxide that will allow us to eliminate the shallow-doped layer," he explains. Very recent results indicate success in making small quantities of cells with efficiencies of 24–25% and improved passivation. Monitoring of the stability of these cells has just begun.

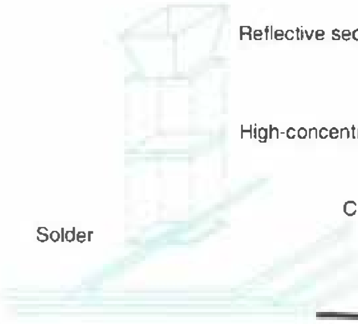
A combination of oxide layers that are resistant to hot-electron damage is the solution that AMONIX has already hit upon, although the company chooses to say no more than that. The Torrance, California, firm is building on its background and experience in making high-performance semiconductors, including microwave transistors and transmitters and also radiation-hardened power semiconductors for space applications. AMONIX is pursuing solar manufacturing for terrestrial as well as space applications.

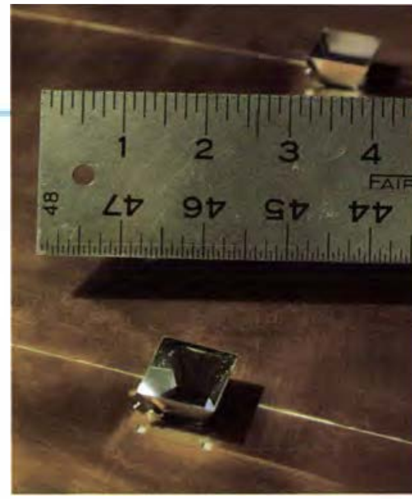
"From our experience making radiation-hardened space devices, we figured that the process of UV damage, although much less intense, must be similar. So we thought the remedy might be similar," says Vahan Garboushian, president of AMONIX. "I can only say that we did not utilize conventional techniques to solve the stability problem."

Garboushian says AMONIX is able to produce stable, 25%-efficient cells today in what it calls a foundry manufacturing environment. Rather than building its own customized wafer fabrication line to produce the solar cells, AMONIX has designed the cell for high-volume, low-cost production by any of several manufacturers of integrated circuits. "This approach gives us instant access to production for which the cost curve is very well established," says Garboushian. "It has shortened the development period and given us production capacity without incurring very high capital costs." Compared with earlier manufacturing designs, as many as four of seven circuit-masking steps are being eliminated.

In the new AMONIX concentrator cell design, the active area (1.2 cm^2) is about double that of the early EPRI-Stanford point-contact device. But because developers believe a lower-cost system may result from operating at a lower concentration to relax optical tolerances and minimize heat dissipation difficulties, the new cell is designed to operate at 260x concentration. This counters much of the effect of the increased cell area, so normal full-power output (about 6.25 W at 25°C) is only slightly higher than with the early cells. AMONIX has produced more than 1000 stable concentrator cells under EPRI contract since 1990, with typical cell efficiencies of 24%. The goal is 26%-efficient, stable cells in high-volume, low-cost production.

EPRI and other researchers have recognized for some time that the establishment of volume manufacturing of cells at an affordable cost was only one step toward the ultimate goal. The other parts of the HCPV system design needed improvement to reduce costs and make the system more readily manufacturable. As it stood in the late 1980s, the system was too complex to become a low-cost product. There were too many pieces to put together in too

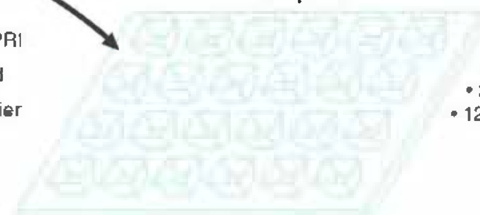


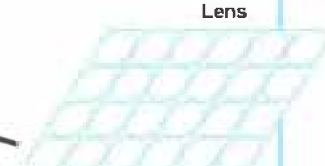


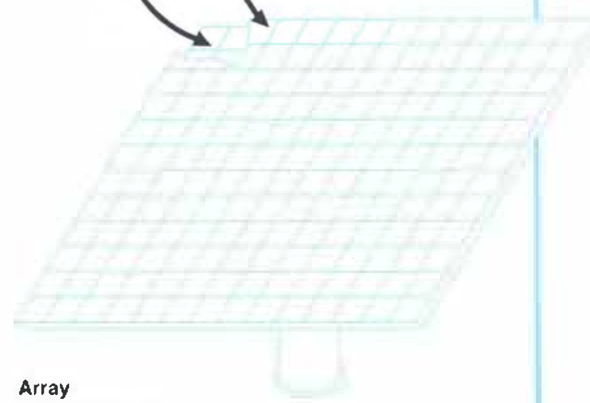
Closeup of cells with SOEs

EPRI Integrated HCPV Array: Nearing Commercialization

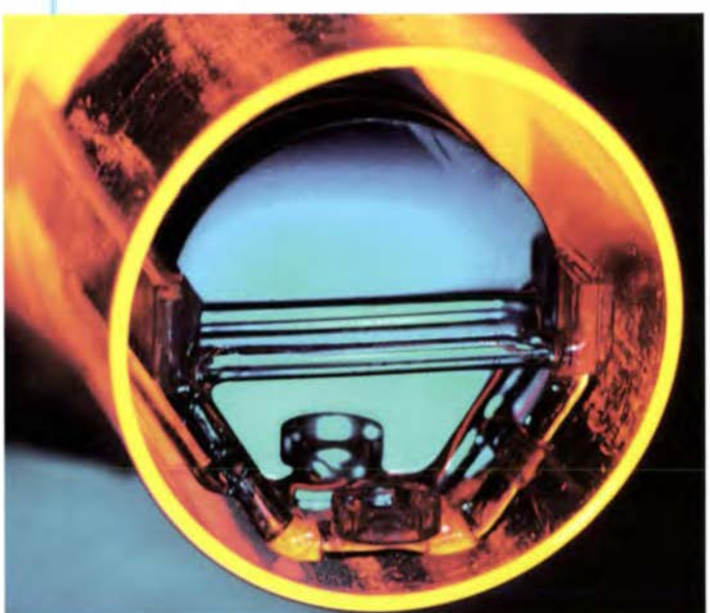
AMONIX, Inc., of Torrance, California, is leading a team of EPRI contractors to complete and commercialize the HCPV cell and integrated array system for which EPRI received a patent earlier this year. At the heart of the integrated array is a new cell mount design that features laminated conductive and insulating layers on top of an aluminum substrate in a printed circuit board–type panel. Individual solar cells (metallized on the bottom side) span gaps in the copper conductive layer. In a full-size, 20-kW array, 168 such panels—each containing 24 cells and secondary optical elements (SOEs)—form the bottom portion of a box-beam structure. The top part of the structure consists of parquets of Fresnel lenses designed for 250X sunlight concentration. Made of molded acrylic, the lenses in each parquet are arranged in a 4 X 6 matrix. A motorized, computer-controlled pedestal keeps the array pointed at the sun.



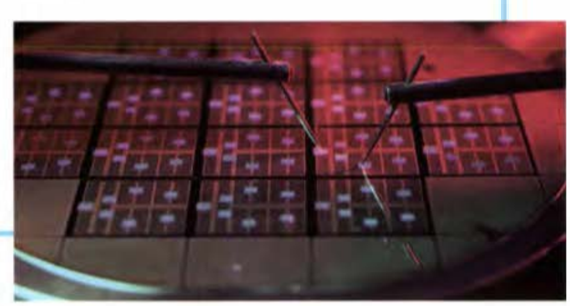




Wafer fabrication and diffusion



Solar cell manufacturing



many steps—the individual cell packages (48 to a module), the modules (60 to an array), and the array itself.

Confident that it had the challenge of making the cells in hand, AMONIX went on to join with other EPRI contractors on a new, low-cost integrated array concept that eliminates parts as well as processing and assembly steps. Indeed, some of AMONIX's earliest stable cells have been delivered to EPRI contractors involved in development work for the HCPV integrated array. Originally developed for EPRI by Cummings Engineering, the concept involves automated attachment of 24 solar cells on a single, printed circuit board–type panel consisting of three laminated layers: an aluminum substrate, an electrically insulative layer, and an electrically conductive layer. Separate parts of the conductive layer form the positive and negative conductors, with each solar cell spanning a gap in the layer and secured by contacts. The design eliminates cell packages and modules, and the cell's backside contact requires only a single solder-mounting step.

A total of 168 such panels form the bottom portion of a box-beam array structure. Above each panel, forming the top surface of the array, are Fresnel lens parquets in a 4 × 6 matrix. The array is then set on a two-axis pedestal with computerized tracking control. "We've adapted the earlier design and eliminated the modules, so we go from cell panels to full arrays in fewer steps," says EPRI's Dostalek.

The integrated array involves one-quarter the number of parts of the earlier design, meaning substantially reduced mass, which allows the surface area to be increased by 50% to about 150 m^2. This boosts peak-rated power to 25 kW per array. Also, most of the welding has been eliminated in favor of screws, rivets, and other features that increase ease and speed of assembly.

AMONIX's Garboushian and EPRI managers say that the now-patented array design shows strong promise for enabling the concentrator technology to achieve an installed system cost of $2/W in substantial manufacturing volume. Work in preparation for installing and testing the first prototype of the new integrated array at Georgia Power's Shenandoah site began this fall, and installation could be completed by mid-1993; researchers hope to have 1 kW of active cells (9 panels) on test in the array by early next year.

Meanwhile, AMONIX has formed an alliance with EPRI contractors Cummings Engineering and Scientific Analysis to commercialize the EPRI technology and integrated array design. The company has begun limited domestic and international marketing. Its next contract is to supply an integrated array to the PG&E-led PVUSA project, which is cosponsored by other utilities, DOE, and EPRI.

Packing them in: another approach

Not only is SunPower working to regain the cell efficiency lost as a result of the interim doped-layer solution to the stability problem, it is proceeding with its own, very different approach to using the concentrator cell technology. EPRI and Sandia have jointly sponsored cell development work at SunPower, but the company continues to search for a business partner that can capitalize further development of its system concepts. SunPower believes its designs, which combine elements of solar-thermal receivers with high-concentration photovoltaics, promise the lowest-cost electricity generation for large bulk power applications.

SunPower has developed a design for a 10-kW dish collector featuring segmented, parabolic mirrors to direct and concentrate light, as well as a design for a larger, 200-kW tower-mounted central receiver faced by a field of reflecting heliostats. At the focal point in each of these system designs are dense arrays of closely spaced concentrator cells capable of operating at 20–30 W/cm^2 and requiring active cooling by water circulation on the back side.

SunPower's dense array designs are based on 150-W modules that consist of 10 monolithically interconnected back-contact solar cells formed on a single 4-inch wafer, along with a substrate, cover glass, and a cold plate that circulates the coolant. The firm has built its own pilot production facility for cell and system manufacturing. It believes that in large-scale production it can bring the installed system cost of its technology in a central receiver configuration down to around $2/W of rated power.

SunPower has tested an early module prototype at Sandia's solar-thermal test facility, recording efficiencies as high as 22%. A 1-kW demonstration dish is under test outside SunPower's headquarters. For a nominal 10-kW dish, the receiver would consist of 72 modules grouped in a 6 × 12 matrix that is positioned at the focal point of a group of segmented, parabolic mirrors. A 200-kW central receiver would require some 6 to 7 ft^2 of modules, mounted on a tower above a field of heliostats.

The company says it believes that heliostats, which have benefited from extensive development under the federally sponsored solar-thermal technology program, offer the lowest-cost means of concentrating sunlight for solar plants of more than a few megawatts of rated power. For now, however, SunPower is looking for a partner to help fund the remaining development of its 10-kW dish receiver. The company has a contract to supply the PVUSA project with two prototypes.

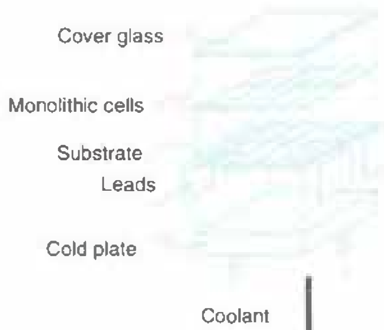
In addition to developing its own HCPV systems, the company could also become a cell and component supplier to other PV system integrators, points out Swanson. SunPower recently began commercially offering 21%-efficient, nonconcentrating, 35-cm^2 flat-plate solar cells based on the EPRI-Stanford technology and intended for specialty applications.

Swanson says he is "very optimistic on the technical side" about the future of HCPV technology. But, he adds, "the issues now are more of financing the development and of whether there is going to be a market for the technology. Our particular system is really designed for large-scale power plants, and that market is very uncertain. There is not much pressure, economic or otherwise, on utilities right now to build such plants at a premium price." He believes that other PV technologies are better suited than HCPV to serve emerging niche and international markets.

Swanson recalls that as a result of government-sponsored development in the

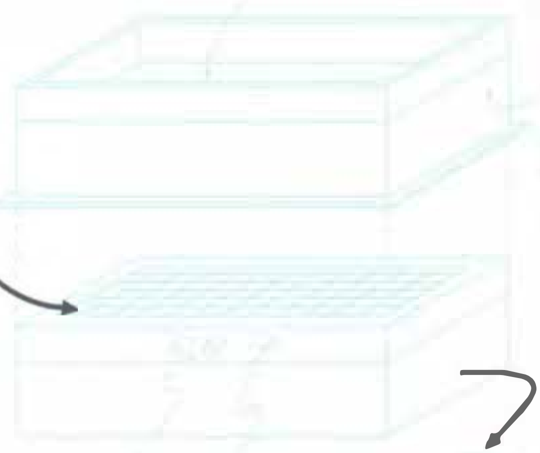
SunPower: Dense Solar Arrays in a Dish

SunPower, Inc., has developed a solar concentrator system based on dense arrays of closely spaced cells with forced cooling. The Sunnyvale, California, company is pursuing the development of a 10-kW parabolic dish reflector that features segmented mirrors. At the focal point of the 72-m^2 aperture dish is a receiver containing 72 modules, each with a power rating of 150 W. Each module consists of a dense array of 10 monolithically integrated solar cells mounted with a cold plate assembly for cooling. Inside the receiver, the individual cold plates are connected by manifolds for the circulation of coolant. A 1-kW prototype dish is currently being tested. For applications of 200 kW or more, SunPower has developed a conceptual design of a larger (6–7 ft^2) receiver that would sit atop a tower at the focal point of a field of sun-tracking heliostats.



Dense array module
- 150 W
- 10 monolithically interconnected back-contact cells
- Cold plate for coolant

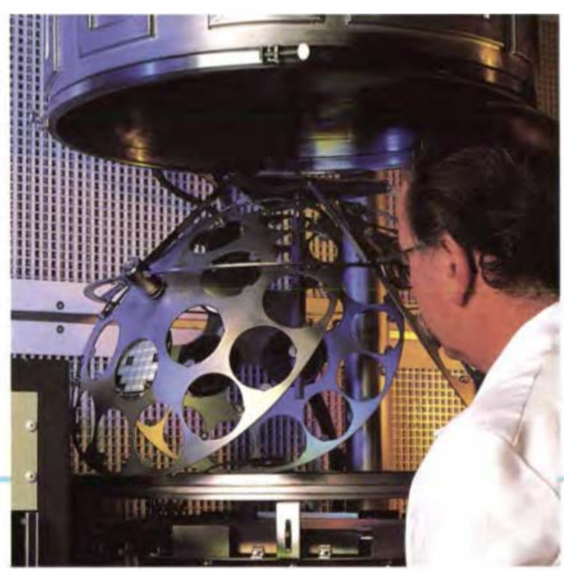
Mockup of 150-W dense array module



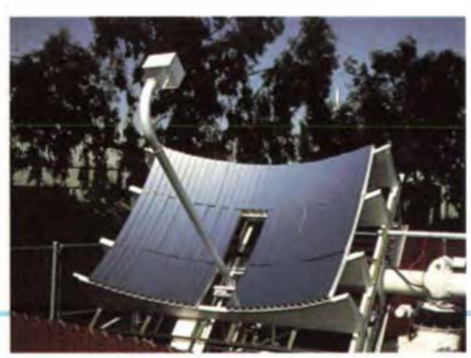
Receiver
- 10 kW at 20°C ambient and 850 W/m^2 direct sunlight
- 6 X 12 matrix of 150-W dense array modules

Parabolic dish
- 268X geometric concentration
- 94 low-iron, second-surface-silvered mirrors
- Two-axis tracking structure
- Mirror aperture area: 72 m^2

Cell fabrication and processing



Prototype 1-kW parabolic dish and receiver



late 1970s, several early, high-cost concentrator arrays rated at 200–300 kW were installed some 10 years ago at several sites, including the Phoenix, Arizona, airport and sites in Saudi Arabia. "The systems we're talking about today are actually smaller scale. So progress with the technology has been painfully slow. And it's still going to be a long haul."

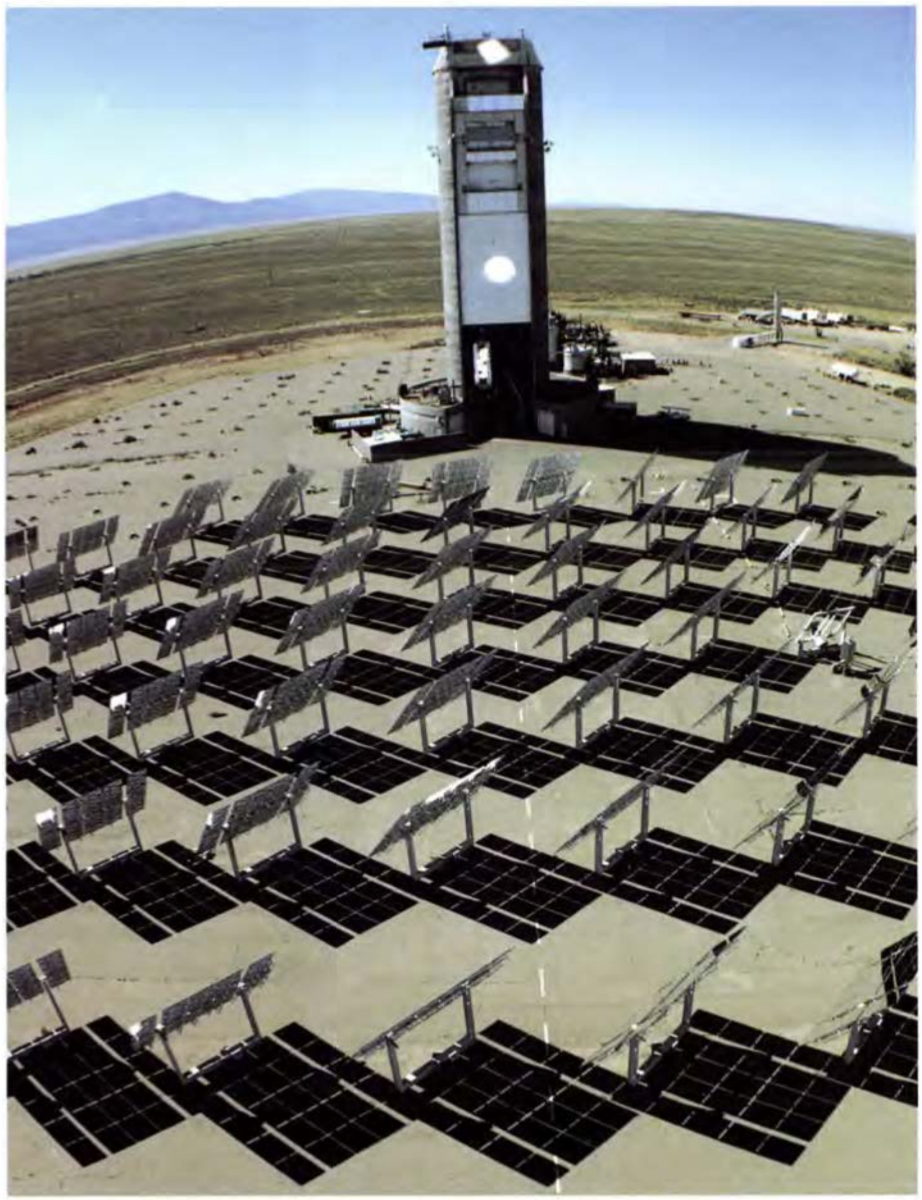
Keeping the technology moving

Despite the recent technical success that is fueling cautious optimism, the future of HCPV technology is not assured. Unlike flat-plate technologies, HCPV has not had the early niche markets—for example, in consumer products and remote power systems—that have kept some PV manufacturers in business and have provided a foothold in emerging international markets while efficiency improvements or cost reductions were pursued. (Some of the companies active in HCPV technology got their start making high-power solar converters for satellites, a field where the profit margin may be high but the volume is low and the market potential is limited.) In the absence of early product revenues, it has been difficult for HCPV companies to attract sufficient capital to sustain R&D or to launch manufacturing in sufficient volume to produce a low-cost product.

Researchers are confident that the installed system cost for HCPV technology will fall to $2 or less per watt of peak-rated power for systems with efficiencies of 15–20% if large-volume production is reached later in this decade. However, there are new doubts about when there will be enough firm market demand for the systems to justify the investment necessary to achieve such production.

Entech line-focus collectors on test

Clean room for device fabrication and process development



Heliostat field and power tower test site

HCPV TECHNOLOGY DEVELOPMENT AT SANDIA

In addition to EPRI's long-running development effort in HCPV, the U.S. Department of Energy has for many years sponsored HCPV and solar-thermal technology development programs at Sandia National Laboratories in New Mexico. The Sandia program includes various laboratory testing and measurement facilities, as well as field test areas that are used in a coordinated effort with program contractors who are pursuing commercial designs for HCPV cells, collectors, and systems. SunPower is among the participants in Sandia's program. A prototype of its dense array has been tested at the solar power tower and heliostat field of Sandia's solar-thermal test facility.

HCPV manufacturers have high hopes that their technology will eventually find widespread application around the world at a variety of deployment scales. Establishing a foothold in some nonutility markets in the near term could be crucial to bringing production costs into the competitive range. Yet HCPV manufacturers realize that the rest of the world is looking to the U.S. utility market to demonstrate the technology's value and reliability under the most demanding service conditions. And unlike the case for other PV technologies, the U.S. utility market for HCPV may be limited to the Sunbelt states.

The technology may be on a clear path to meeting the manufacturing cost and efficiency goals established over a decade ago—goals that were designed to lead to costs of 6–8¢/kWh for PV-generated electricity. But a decade of excess availability of natural gas and low oil prices (compared with the 1970s) has helped raise the near-term hurdle for economic competitiveness for photovoltaics still higher. Even if high-performance, 20%-efficient HCPV systems were commercially available now for $2000/kW, in most cases utilities, under regulatory mandates to pursue least-cost supply planning, have several more-economic options for meeting or managing peak and intermediate electricity demand. Developers of the technology understand that the installed cost will eventually have to be driven below $2/W for significant use in bulk power generation to occur.

Still, says DeMeo, "more than 50 U.S. utilities today are finding many small-scale applications for conventional photovoltaics as remote power sources in their own operations or for supplemental customer service. Utilities are gaining increasing familiarity with and appreciation for the technology, which many see as having tremendous potential in the long run.

"Utilities such as PG&E are considering installing PV in small amounts for distribution feeder support. Even utilities that do not have good solar resources recognize that if PV can become economically competitive and begin to make a significant contribution to the nation's bulk power supply elsewhere in the country over the next decade, that could displace some fossil fuels, leaving more available in the market than there might be otherwise."

HCPV technology has held on for more than a decade while government- and EPRI-sponsored research programs continued pushing it toward now-outdated cost and efficiency goals that were set when rapidly rising fossil fuel prices made the arrival of economic competitiveness seem much closer at hand. The technology has almost reached those goals, but now the timing and size of the market for HCPV have become less certain. Nevertheless, EPRI's Birk believes that "HCPV may prove to be an invaluable option for utilities who do not wish to tie their future exclusively to conventional fuels, with the concomitant uncertainty in long-term availability, cost, and governmental policy."

Beyond the prototype development and demonstration test units planned over the next few years, how to best sustain the technology is now becoming a focus for both EPRI's solar concentrator program and the larger effort managed by Sandia National Laboratories for DOE. Over the next two years, Sandia will be winding down contract work with about eight cell and system manufacturers that have been involved in a $12.4 million cofunded effort begun in 1990—the Concentrator Initiative Program.

In addition to SunPower, the solar cell manufacturers involved in Sandia's program include Solarex, a subsidiary of Amoco; Applied Solar Energy Corporation; and Hughes Aircraft's Spectrolab subsidiary (originally a manufacturer of solar cells for satellite power). Alex Maish, a Sandia project leader, says they are all working with manufacturers of terrestrial collectors to commercialize the concentrator technology.

"The technology itself is very exciting, and it is encouraging that all of the companies we've been working with are committed to commercializing their products. They are still making great strides both technically and in the business sense of becoming viable companies. But whether they will succeed in commercializing the technology depends on many factors, some of which are beyond the control of Sandia or even these companies," says Maish.

Tom Bickel, Sandia department manager for photovoltaic technology, adds that "Sandia and EPRI need to expedite the development of concentrator technology and help the startup companies identify near-term markets." In fact, the two organizations have begun exploring ways to pool resources to further advance the concentrator field as well as other areas in photovoltaics. "We look forward to working more closely with EPRI to try to get this technology up and running," says Bickel.

In sum, both the technical status of HCPV technology and its prospects have advanced substantially over the past several years, according to EPRI's DeMeo. "Because of the performance demonstrated in components so far and the prospects for cost reduction through streamlining that is just beginning," he says, "this could be the first PV technology to enter the bulk power arena. The key challenge for all of us in the concentrator community—industry, government, and utilities—is to build a bridge to utility-grade power through market entry efforts to provide early experience, generate revenue, and reduce system costs. We will know within the next five years whether this challenge can be met." ■

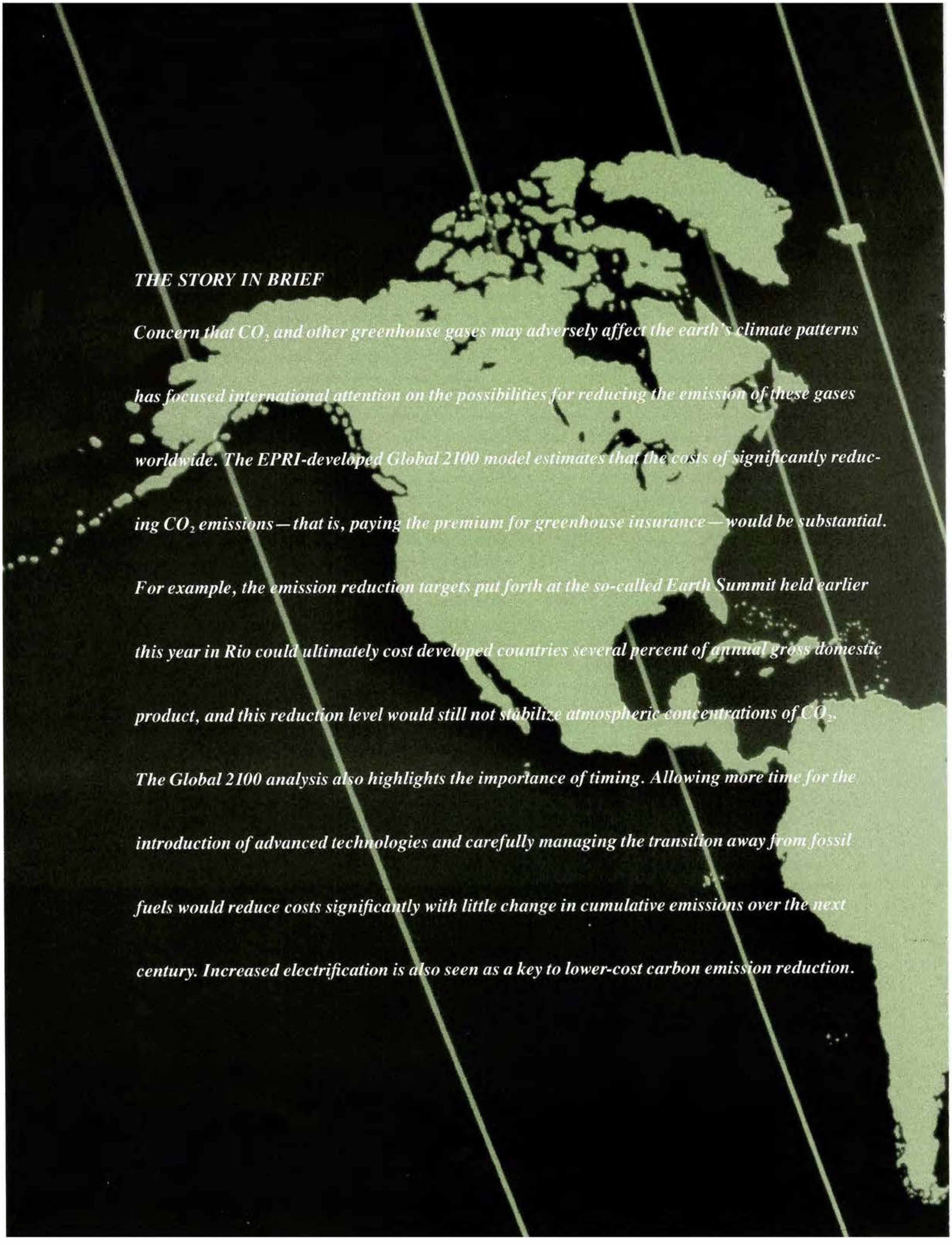
Further reading

A Summary of Recent Advances in the EPRI High-Concentration Photovoltaic Program, Vols. 1 and 2. Interim report for RP1415-9, prepared by Daedalus Associates. March 1992. EPRI TR-100392.

Development Efforts on Silicon Solar Cells. Final report for RP790-2, prepared by Stanford University. February 1992. EPRI TR-100403.

"Opening the Door for Utility Photovoltaics." *EPRI Journal*, Vol. 12, No. 1 (January–February 1987), pp. 4–15.

Background information for this article was provided by Edgar DeMeo, Frank Dostalek, and Frank Goodman, Generation & Storage Division.

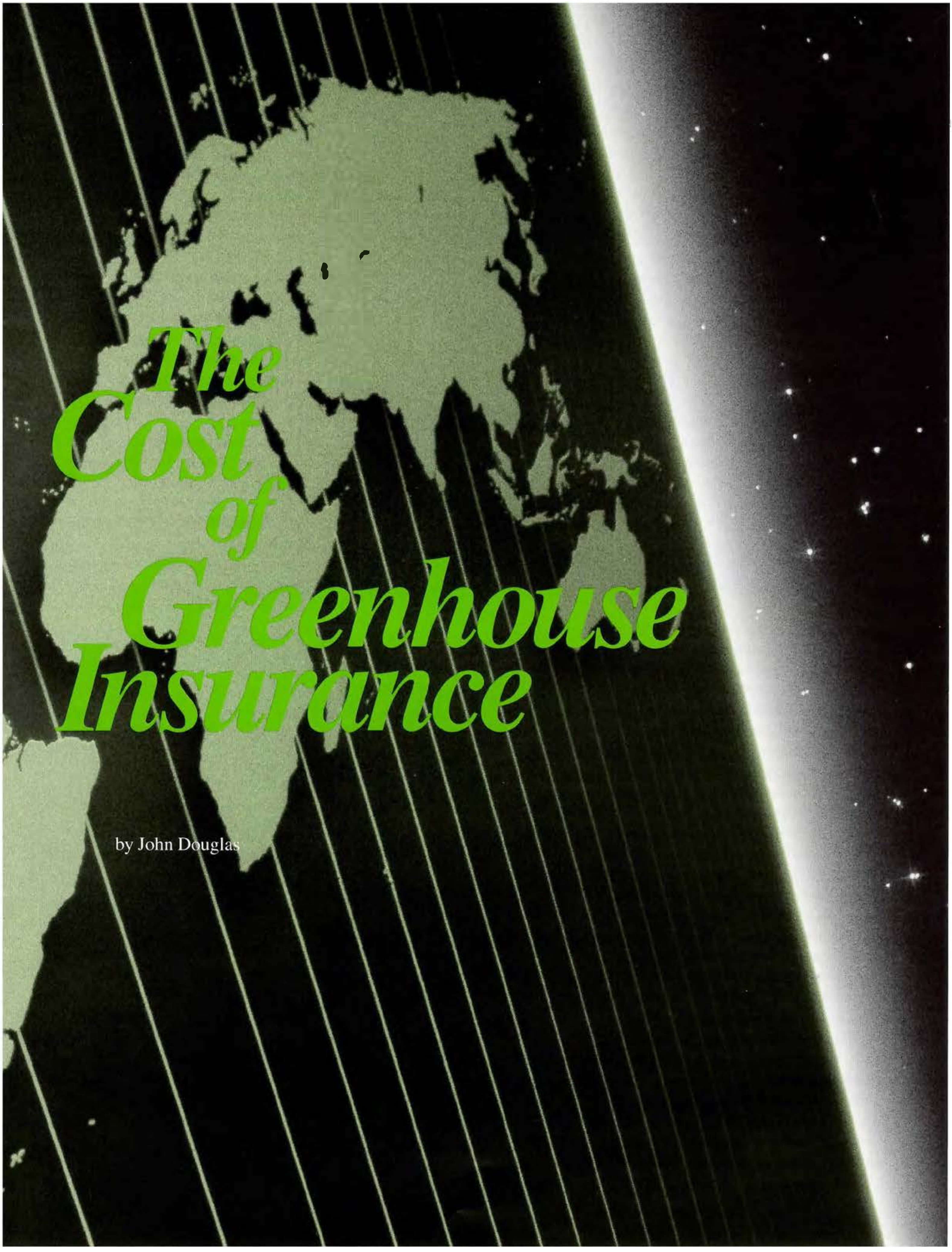


THE STORY IN BRIEF

Concern that CO_2 and other greenhouse gases may adversely affect the earth's climate patterns has focused international attention on the possibilities for reducing the emission of these gases worldwide. The EPRI-developed Global 2100 model estimates that the costs of significantly reducing CO_2 emissions—that is, paying the premium for greenhouse insurance—would be substantial. For example, the emission reduction targets put forth at the so-called Earth Summit held earlier this year in Rio could ultimately cost developed countries several percent of annual gross domestic product, and this reduction level would still not stabilize atmospheric concentrations of CO_2. The Global 2100 analysis also highlights the importance of timing. Allowing more time for the introduction of advanced technologies and carefully managing the transition away from fossil fuels would reduce costs significantly with little change in cumulative emissions over the next century. Increased electrification is also seen as a key to lower-cost carbon emission reduction.

The Cost of Greenhouse Insurance

by John Douglas



IN RECENT YEARS THERE HAS BEEN GROWING CONCERN that the accumulation of greenhouse gases in the earth's atmosphere may lead to undesirable changes in global climate. This concern has led to a number of proposals, both in the United States and internationally, to set physical targets for limiting greenhouse gas emissions. With carbon dioxide (CO_2) believed to be responsible for over half of the human contribution to greenhouse gas emissions, the energy sector plays an important role in strategies to address potential climate change.

Sensible greenhouse policy requires balancing benefits and costs. Fossil fuels provide more than 90% of the world's commercial energy. Before committing to a path that would require a major restructuring of the world's energy system, therefore, decision makers must address two questions: What would reductions in emissions buy in terms of reduced environmental damage? And what would be the price tag?

Neither question has a straightforward answer. At present, huge gaps remain in our understanding of the physical and biological processes that influence the climate system. There is growing agreement that increased concentrations of greenhouse gases will lead to global warming—but the extent, time frame, and regional impacts remain unclear.

Considerable uncertainty also persists regarding the costs of measures to limit emissions. Proponents of immediate controls argue that ample low-cost alternatives to carbon-intensive fuels are readily available. All that is needed, they say, is the political will to engineer the transition to a low-carbon economy.

Many economists, however, are less sanguine about the costs of emission abatement. If economically attractive options are available, they argue, what is preventing these alternatives from automatically entering the marketplace? They also fear that a *rapid* transition away from carbon-intensive fuels would be extremely costly.

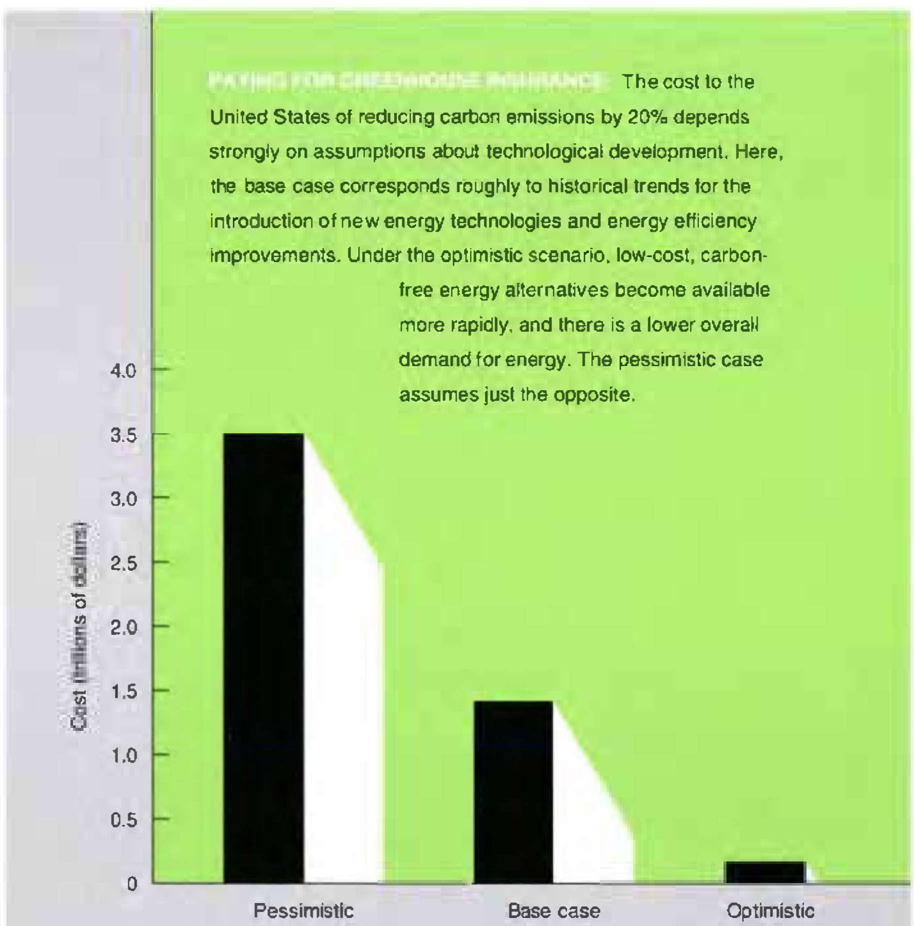
These differing opinions present a dilemma for policymakers, since a case could be made for or against emission reductions. Addressing the issue is like deciding whether to purchase an insurance policy: If the cost is negligible and the risks are considered great, there is little reason not to buy. But if the insurance premium is expensive—that is, if there is a significant price tag attached to limiting the emission of man-made greenhouse gases—then it may be worthwhile to pursue alternatives to immediate cutbacks. These alternatives include an intensified commitment to research that could reduce climate uncertainty and research that could lead to the development of new energy supply and conservation technologies.

A series of recent studies conducted with EPRI funding has focused on developing a better understanding of the costs of limiting carbon emissions. The results of this research were recently published in *Buying Greenhouse Insurance: The Economic Costs of Carbon Dioxide Emission Limits* (MIT Press, 1992) by Alan Manne of Stanford University and Richard Richels of EPRI.

Richels summarizes some of the main findings about the costs of limiting carbon emissions like this: "The bad news is that if significant emission limits are required, the costs are likely to be substantial—perhaps as large as several percent of the annual gross domestic product. The good news is that the size of the ultimate bill can be significantly reduced through successful R&D in both the supply and demand sides of the energy sector." Richels notes that timing will also be critical. "Forcing a rapid transition away from fossil fuels would be *very* expensive. If it turns out that substantial reductions in CO_2 emissions are called for, it's important that time be allowed for a managed transition." Finally, he stresses the importance of electricity during such a transition. "Our analysis points to increased electrification as the least-cost way to reduce carbon emissions from the energy sector in the long run."

Buying greenhouse "insurance"

The whole greenhouse issue is fraught with uncertainty—about what climate changes might actually result from in-



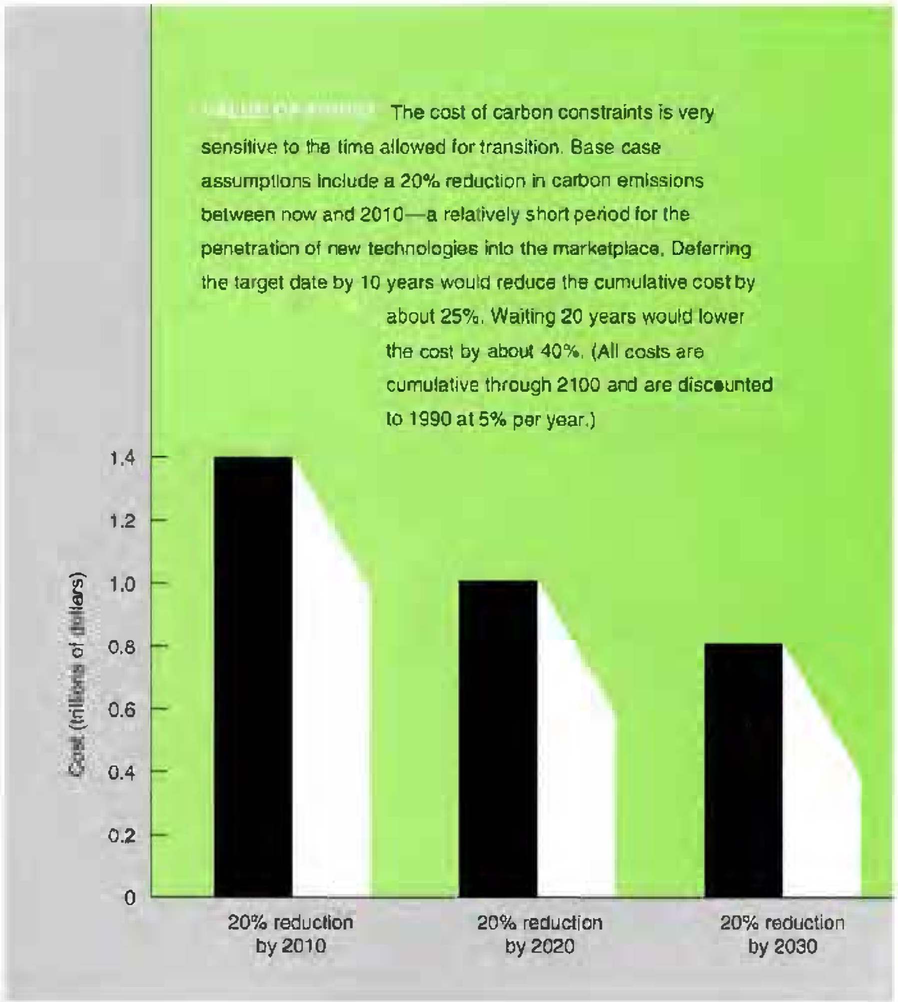
[illegible] The cost to the United States of reducing carbon emissions by 20% depends strongly on assumptions about technological development. Here, the base case corresponds roughly to historical trends for the introduction of new energy technologies and energy efficiency improvements. Under the optimistic scenario, low-cost, carbon-free energy alternatives become available more rapidly, and there is a lower overall demand for energy. The pessimistic case assumes just the opposite.

creasing carbon emissions, when these changes might occur, and what their effects might be. The atmospheric models used to forecast climate have several important shortcomings, including poor spatial resolution, inadequate accounting for feedback mechanisms, and insufficient treatment of such factors as variations in solar output, volcanic activity, and the earth's reflectivity. Nevertheless, these models generally indicate that a doubling of atmospheric greenhouse gas concentrations from their pre-Industrial Revolution levels—expected within the next century unless extraordinary measures are taken to reduce emissions—would increase average global temperatures by 1.5–4.5°C (2.7–8.1°F).

Possible consequences might include changes in crop productivity around the world, migration of forest ecosystems, a rise in sea level, and extinction of some endangered species. None of these impacts is certain, however. Although a growing amount of research is being done, information about impacts is still at a rudimentary stage, and the environmental, economic, and social consequences of global warming remain uncertain.

In such a context of great uncertainty and potential risk, there have been a variety of proposals to buy "insurance" against global warming by reducing greenhouse gas emissions as soon as possible. At the United Nations Conference on Environment and Development—the so-called Earth Summit—held in Rio de Janeiro earlier this year, the United States and more than 150 other countries signed the Framework Convention on Climate Change, committing themselves to adopt policies to control greenhouse gas emissions but setting no specific deadlines.

One policy mechanism frequently suggested as a way to bring about emission reductions is the carbon tax. Such a tax would be levied on the combustion of fuels according to their carbon emission intensity, in effect raising the cost of energy consumption to end users. Coal would be particularly penalized, since it produces 21% more CO_2 than oil per unit of energy consumption and 76% more than natural gas. The size of the carbon tax that would be needed to bring about specific emission reductions has been hotly debated, however, as have the cost and availability of noncarbon alternatives and the speed with which demand-side efficiency can be improved. In the absence of a carbon tax or similar restrictions, in many countries coal would most likely maintain its dominant role, particularly in the nonelectric energy sector, owing to the depletion of supplies of conventional oil and gas during the coming century.



The cost of carbon constraints is very sensitive to the time allowed for transition. Base case assumptions include a 20% reduction in carbon emissions between now and 2010—a relatively short period for the penetration of new technologies into the marketplace. Deferring the target date by 10 years would reduce the cumulative cost by about 25%. Waiting 20 years would lower the cost by about 40%. (All costs are cumulative through 2100 and are discounted to 1990 at 5% per year.)

Manne and Richels have focused on the costs of reducing carbon emissions and have examined some of the energy supply and demand issues involved in implementing such reductions. With EPRI funding, they have developed a computer model of CO_2-energy-economy interactions called Global 2100. This model can analyze the effects of specific carbon emission quotas for each of five major geopolitical regions and simulate their effects on regional economies. An energy technology assessment submodel makes it possible to evaluate the effects of introducing new technologies, including the effects of the speed at which they replace older, more carbon-intensive technologies. Using Global 2100, the researchers have also explored the costs associated with various carbon tax and technology-forcing strategies that might be adopted here and abroad.

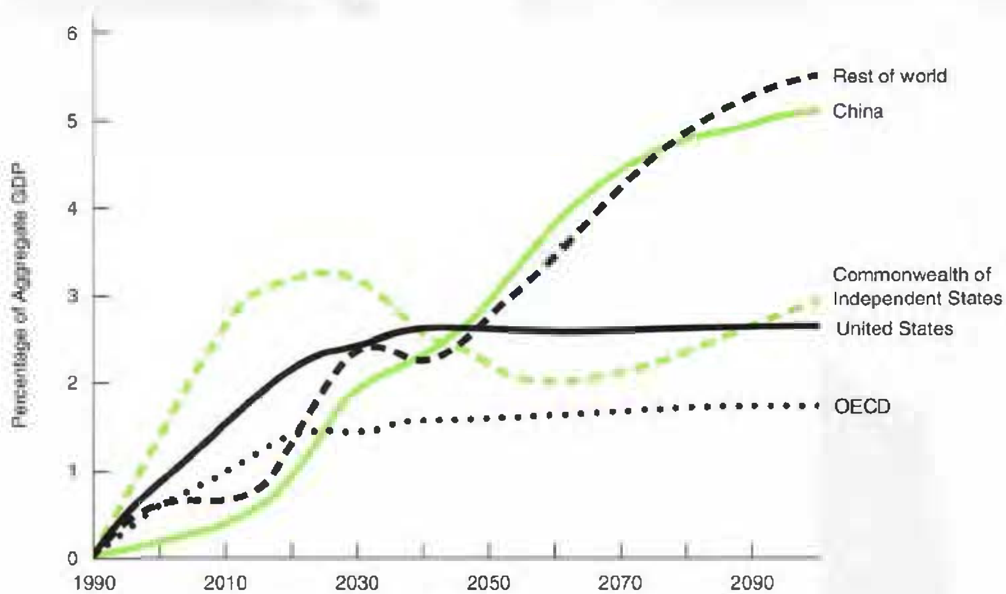
Much of their recent work has focused on assessing the costs of the so-called global stabilization scenario, currently being considered at a number of international meetings. This scenario assumes stabilization of global emissions at 1990 levels. Richels notes that "there is clearly no unique formula for achieving global stabilization of emissions. Most proposals recognize the need for some growth in CO_2 emissions in developing countries, where per capita emissions are very low in comparison with developed countries." One widely discussed proposal involves having developed countries cut back emissions by 20% and letting levels in developing countries increase modestly—which would result in net global emission

Global Implications of Carbon Limits

To determine the international effects of carbon constraints, Alan Manne and Richard Richels have analyzed the proposal to stabilize global carbon emissions by imposing a 20% cutback in industrialized nations while allowing developing countries to increase emissions by 50%. Even with this differential to allow for faster economic growth, developing countries would eventually pay a higher price in terms of reduced gross domestic product (GDP). For the United States and other industrialized nations, the cost of emission controls would run between 1% and 3% of annual GDP for most of the century. The costs to China and other developing countries would rise to 5–6%.

"The costs are higher for developing countries because their economies are growing faster," explains Richels. "Both population growth and economic expansion will continue to put upward pressure on the energy demands in these countries. And the cost of any restriction on carbon emissions will fall most heavily on countries, such as China, that are hoping to fuel economic expansion with an energy resource base dominated by coal."

Global patterns of CO_2 emissions will also shift significantly under the assumptions of this analysis. In 1990, the industrialized nations accounted for 64% of total emissions; their contribution is expected to drop to 30% by 2100. Since economic growth rates are considerably higher in the developing countries, those countries will also have higher growth rates in energy consumption and carbon emissions. □



A GLOBAL PERSPECTIVE The relative economic burden of stabilizing global carbon emissions will differ significantly among various countries and regions of the world. For a scenario in which developed countries reduce emissions by 20% and developing countries are permitted a 50% increase over the next century, the annual gross domestic product (GDP) losses to the United States would be about 2.5%, and other industrialized nations (OECD) would lose about 1.5%. China and other developing countries, however, would eventually be penalized by 5–6% of their annual GDP because of rapid economic growth rates and, in some cases, greater dependence on coal resources.

stabilization. Manne and Richels examined this proposal extensively as part of the recent Energy Modeling Forum Study at Stanford University.

Paying the premium

The costs of reducing greenhouse emissions—that is, paying the premium for greenhouse insurance—would indeed be substantial if the United States followed the scenario just described. By the time the targeted 20% reduction in emissions was achieved in 2010, the resulting annual losses in the U.S. gross domestic product (GDP) would exceed 1%. By 2020 this annual penalty would rise to a stable level of 2.5%. Adding up the losses over all the years from 1990 to 2100, Manne and Richels found that their present value would be $1.4 trillion (discounted to 1990 at 5% per year).

According to the analysis, GDP losses for other industrialized countries following the 20% reduction scenario would be similar (in percentage terms) to those of the United States, but many developing countries would ultimately be more severely affected economically even if they were allowed a modest increase in their carbon emissions over the next century (see sidebar).

Manne and Richels also examined the size of the carbon tax that would be necessary to bring about emission changes of this magnitude. The purpose of the carbon tax would be to raise the price of fossil fuels sufficiently that consumers would switch to less carbon-intensive alternatives. Richels notes that a tax on the order of $135 per ton of carbon would be needed in the United States by the year 2000 because, "with the limited availability of low-carbon alternatives, consumers would be willing to pay a high price to burn fossil fuels." The tax would have to climb even higher—up to $300 per ton—in the early decades of the next century, owing to the exhaustion of low-cost gas resources and inexpensive sources of conservation. Eventually the tax would stabilize at approximately $200 per ton as a variety of carbon-free alternatives become available. A recent study by the U.S. Department of Energy shows how a carbon tax of $100 per ton would affect the price of various fuels (see table).

EFFECT OF A CARBON TAX The cost added to various fuels by imposing a carbon emission tax would depend on their relative carbon content. Coal would be penalized most; natural gas, least. The cost additions shown here represent a tax of $100 per ton of carbon.

Fuel	Base Cost	Added Cost	Added Cost (% of base)
Crude Oil	$16.01/bbl	$12.19/bbl	73%
Gasoline	$0.98/gal	$0.26/gal	27%
Heating oil (distillate)	$0.89/gal	$0.29/gal	33%
Wellhead natural gas	$1.81/tcf	$1.49/tcf	82%
Residential natural gas	$5.87/tcf	$1.50/tcf	25%
Minemouth coal	$23.02/short ton	$55.33/short ton	240%
Utility coal	$33.51/short ton	$55.33/short ton	165%
Electricity	6.5¢/kWh	1.76¢/kWh	27%

Source: U.S. Department of Energy.

The Manne-Richels analysis is based on what the authors believe to be realistic assumptions about the potential for supply- and demand-side improvements in the energy sector during the coming decades. However, they stress that technology forecasting is a tricky business, and they show the sensitivity of their findings to alternative sets of assumptions. Richels notes, "If one subscribes to a more pessimistic view of the future, the costs can be considerably higher."

The century-long cumulative costs of reducing carbon emissions under base case assumptions would be $1.4 trillion. In a more pessimistic scenario, high energy demand and greater dependence on carbon-intensive fuels would combine to increase discounted losses to over $3.5 trillion. Alternatively, under a scenario with highly optimistic projections about the potential for supply enhancements and efficiency improvements, discounted losses would be much lower—about $200 billion.

It is important to note that under a global emission stabilization plan, actual atmospheric concentrations of CO_2 would continue to increase, albeit more slowly than in the past. Thus, achieving stabilization of emissions cannot be seen as the "solution" to greenhouse issues. The more aggressive goal of stabilizing atmospheric concentrations of CO_2 would require much more drastic and expensive global action—a cutback in emissions of about 70%, according to the Intergovernmental Panel on Climate Change. Stabilizing atmospheric concentrations is the stated objective of the United Nations Framework Convention on Climate Change, which President Bush signed in Rio last June.

A question of timing

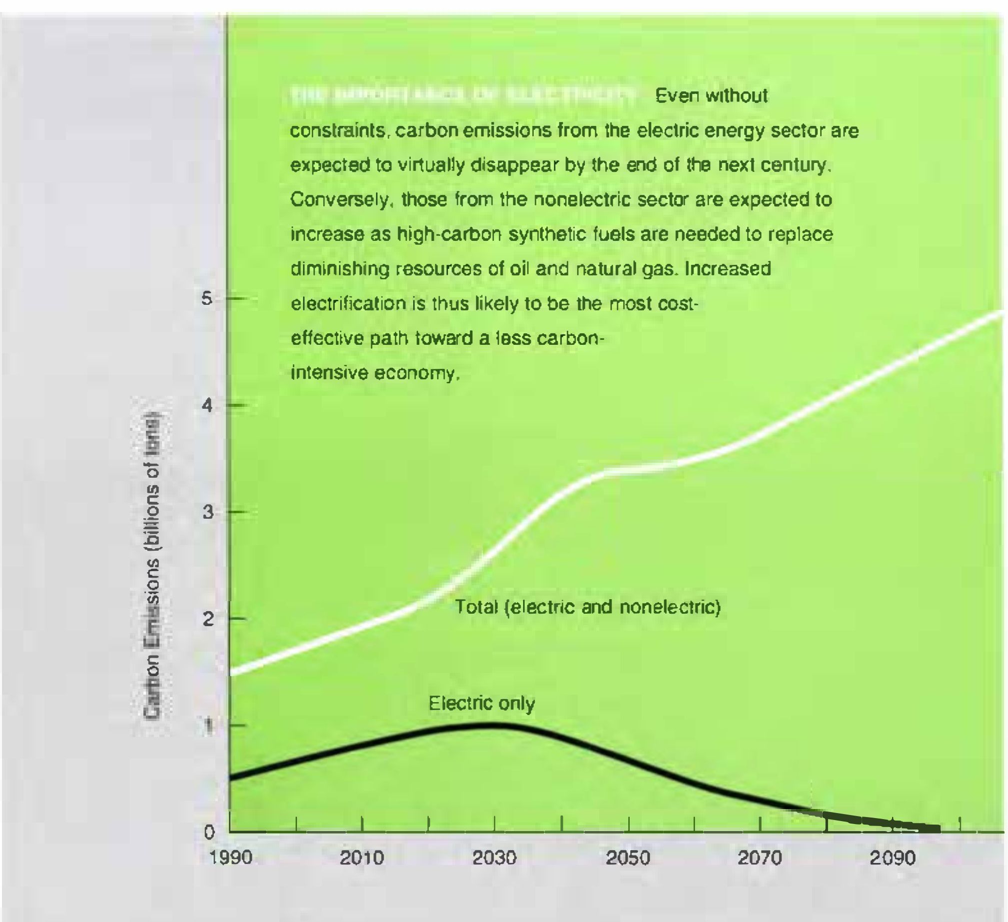
A major reason that the costs of reducing carbon emissions are likely to be high in the scenarios just discussed is that the target date set for achieving a stable 20% reduction is 2010—a relatively short time compared with either the rate of technological development or the rate at which major energy facilities are replaced. In another recent study, Manne and Richels asked, What if the United States had more time to manage the transition away from fossil fuels? What would be the effect on total costs? What would be the effect on total emissions?

When Manne and Richels analyzed these questions, they found that a 10-year delay in achieving emission targets would lower the total cost by about 25%; a 20-year delay would lower the cost by about 40%. "This result should come as no surprise," comments Richels. "The time required for large-scale deployment of new energy supply technologies is typically measured in decades. Widespread adoption of higher-efficiency end-use technologies also takes time, since these are often embedded in long-lived structures or equipment—such as houses, factories, and automobiles—that will not be replaced instantaneously. The process can be accelerated, but only at a substantial cost."

The effect of such deferrals on cumulative U.S. carbon emissions over the next century would be small, according to the analysis. Moving the target date by 10 years would increase total emissions for the century by only 3–4%, while a 20-year delay would result in an increase of about 9%.

A perspective on the potential climate impact of delay is provided by Michael Schlesinger and Xingjian Jiang of the University of Illinois, writing in the March 21, 1991, issue of *Nature*. Using a variety of scenarios for reducing carbon emissions, these researchers found that a 10-year delay in implementation would still lead to achieving about 95% of the reduction in warming in the year 2100. The researchers conclude, "This indicates that the penalty is small for a 10-year delay in initiating the transition to a regime in which greenhouse gas emissions are reduced."

In addition to providing more time for market penetration of new technologies, a more managed transition away from fossil fuels would also give scientists more time to reduce some of the climate-related uncertainties that now pose a dilemma for policymakers. Specifically, the Global 2100 model indicates that even relatively small improvements in the ability to predict climate consequences could yield substantial dividends, and that the value of additional information could be more than $100 billion for the United States alone. The benefits come from being able to chart the best course of action for the energy sector and to better focus precautionary steps in the face of uncertainty.



THE IMPORTANCE OF ELECTRICITY Even without constraints, carbon emissions from the electric energy sector are expected to virtually disappear by the end of the next century. Conversely, those from the nonelectric sector are expected to increase as high-carbon synthetic fuels are needed to replace diminishing resources of oil and natural gas. Increased electrification is thus likely to be the most cost-effective path toward a less carbon-intensive economy.

The value of R&D

Technological development continues to provide one of the bright spots in the analysis of the greenhouse issue. Compared with the cost of either a carbon constraint or the potential impacts of global warming, the cost of the R&D needed to produce new energy technologies is small indeed. Without trying to specify which technologies are most likely to succeed, the Manne-Richels analysis dramatically illustrates how important their overall contribution could be.

On the demand side, technological improvements offer the promise of higher efficiency and a further decoupling of economic growth from energy consumption. Manne and Richels found that further investment in this area could have an enormous payoff. For example, doubling the rate of exogenous (not price-induced) efficiency improvements could nearly halve the costs of a carbon constraint.

The biggest long-term payoff will come from successful R&D on the supply side. As crude oil reserves are depleted, coal-based synthetic fuels will become competitive. But such synthetic substitutes produce twice as much CO_2 per unit of useful energy as oil and would thus be penalized severely by a carbon constraint. The development of lower-cost renewable fuels, such as ethanol produced from biomass, could provide a noncarbon alternative, but serious questions remain about the size of their potential contribution because of such factors as competing uses for land and water resources. The possible contribution of renewable fuels in the carbon-constrained analysis was assumed to be 10 quads per year. As a point of reference, in 1990 the total U.S. primary energy consumption was 82 quads per year, and oil imports were running at an annual rate of 15 quads. If the contribution from low-cost renewables could be doubled, however, the cumulative cost of reducing carbon emissions could be lowered by more than one-third.

Fortunately, there are a number of promising carbon-free electricity-generating alternatives. Among these new technologies are direct solar conversion, wind, advanced nuclear reactors, and biomass conversion. Without trying to predict the contributions of specific technologies, Manne and Richels estimate that if the cost of electricity from carbon-free alternatives could be made competitive with that of electricity from new coal-fired power plants, the cost of a carbon constraint could be reduced by more than one-third.

The role of electricity

In their analysis, Manne and Richels assume that environmental concerns will eventually stimulate the development of economically competitive alternatives to coal-fired power plants. As a result, they project that the electricity sector will gradually become less carbon-intensive, even in the absence of measures to limit CO_2 emissions. This is not the case for the nonelectric energy sector. As mentioned earlier, when conventional oil resources are exhausted, they are all likely to be replaced with even more carbon-intensive synthetic fuels. This means that—in the absence of measures to limit CO_2 emissions—the nonelectric sector is likely to become more carbon-intensive over time.

"What this tells us is that if we are really serious about bringing down total carbon emissions, electrification should be an important part of the strategy," says Richels. "Electric and nonelectric energy can be substituted for one another in many markets. Electric heat pumps, for example, offer an alternative to residential oil burners. Electric vehicles offer an alternative to the internal combustion engine. Such interfuel substitution could lower carbon emissions. But economically competitive, long-term alternatives to coal-fired power generation must be available in sufficient quantities to make a difference. Again I want to emphasize the importance of timing: the transition to a more electricity-intensive energy economy based on carbon-free generation can't be accomplished overnight."

Informing the debate

Manne and Richels stress that their work focuses on the size of the insurance premium. Proponents of immediate controls argue that even a high cost of reducing CO_2 emissions may be cheap in comparison with the damage wrought by climate change. Given the uncertainty surrounding the whole greenhouse issue, the question of costs associated with climate change is impossible to answer with any degree of precision, and it was not within the scope of the Manne-Richels analyses. One of the few economists who has ventured out on this shaky analytical limb is William Nordhaus of Yale University, who concludes bluntly, "The economic impact upon the U.S. economy of the climatic changes induced by a doubling of CO_2 concentrations is likely to be small" ("Economic Approaches to Greenhouse Warming," in *Global Warming: Economic Policy Responses*, edited by Rudiger Dornbusch and James M. Poterba and published by MIT Press, 1991). His analysis assumes that only about 3% of the U.S. national income is derived from activities with a potential to be severely affected by climate change, and that another 10% could be moderately affected. On the basis of these assumptions, he estimates that a doubling of CO_2 would produce a change of only about one-quarter of one percent of the national income.

These results are quite preliminary, and much additional work is needed. In describing his estimates, Nordhaus cautions that because current studies tend to omit potentially important effects, his estimate has a large margin of uncertainty. He also notes that the impact might be higher in some developing countries—those more dependent on an agricultural economy, for example. But he observes that the climate sensitivity of these countries will decrease sharply during the next century as they continue to industrialize.

Although the electric power industry is likely to be among the sectors of the U.S. economy most affected by reductions in carbon emissions, Manne and Richels explored a much broader range of implications. As a consequence, the results of their research have been widely cited in a variety of national and international greenhouse policy studies, including the President's Economic Report to Congress, the National Academy of Sciences study of climate change, the Intergovernmental Panel on Climate Change report prepared for the Earth Summit, and various Department of Energy reports. Such recognition has helped focus the attention of policymakers on the potential costs of carbon constraints and the importance of electrification in any strategy for mitigating the greenhouse effect.

"Our goal," concludes Richels, "is to help inform the debate by focusing on an area that has received insufficient attention. Without better information on the cost of emission abatement, it is difficult for policymakers to assess the feasibility of alternative proposals and to determine which measures might be most cost-effective. We've tried to provide such insights without taking sides in the policy debate itself." ■

Background information for this article was provided by Richard Richels, Integrated Energy Systems Division.

TECH TRANSFER NEWS

EPRI Dedicates Mobile Simulator

At a ceremony held on October 29, EPRI and Duke Power Company dedicated the Duke-EPRI mobile simulator, designed for fossil plant operator training and controls engineering. About 100 utility people attended the event, including operators, engineers, and trainers from across the country.

Jointly developed by EPRI and Duke Power, the mobile simulator—housed in two 32-foot trailers that can travel to specific sites—will be available for the use of all EPRI members starting next fall. At the dedication ceremony, the simulator received a technology achievement award from the Society for Computer Simulation. The facility was developed to help operators become proficient with the advanced computer control systems (called soft controls) that are replacing conventional, hard-panel control systems (called hard controls) in power plants across the country. The simulator is also geared toward helping engineers analyze, design, debug, and fine-tune control systems before they are implemented. Using the mobile simulator can save utilities several million dollars. Duke Power estimates that it will save $176 million over the next 15 years through improved controls engineering and the implementation of simulator-based training for control room operators, maintenance technicians, and plant engineers.

Like many other utilities today, Duke Power is replacing all its old pneumatic and analog power plant control systems with distributed control systems. This is a significant transition for plant operators. The old control systems featured long panels with switches, dials, lights, and gages. By contrast, the new system offers a plant operator access to everything through a few computer monitors with touch-screen capability. "Rather than 20 feet of control board, this person is going to be operating through a 20-inch CRT," says Roy Fray of EPRI, manager of simulators and training.

Utilities have been replacing their old control systems with digital, electronic technology since the early 1980s. Conventional simulators designed to train fossil plant operators were costly for utilities, running about $2 million to $4 million, Fray says. Personal computer technology and modern modular modeling have helped bring down the cost of simulator technology to about $500,000 to $700,000.

The Duke-EPRI simulator can be used to train operators already working with the advanced electronic control systems, as well as those who are about to make the transition. And as Fray points out, it can even be programmed to simulate conventional control systems, so new operators can be trained to use those systems.

One advantage of the Duke-EPRI simulator is that it can simulate several different facilities. By contrast, a conventional simulator can simulate only a single plant. Because of this advantage, the new simulator technology makes it economically feasible to train a diverse group of power plant employees in widely scattered plants. Among other benefits, better-trained operators can save fuel during unit startups; startups can be speeded up, allowing more time for generation; and unit trips and downtime can be reduced. "We expect our operators to be able to pay more attention to what the plant instrumentation tells them about the health of the plant and to be able to take timely action to ensure that small problems remain small and large problems never occur," says M. D. McIntosh, vice president of Duke's Fossil/Hydro Generation Department.

EPRI has full-time use of the Duke-EPRI mobile simulator for two years, beginning in the fall of 1993. After that, the Institute will have access to the simulator for 1000 hours a year. EPRI plans to make the simulator available to other member utilities for operator training, training program development, control system design and validation, and simulator development, among other applications. In fact, the Institute recently issued a request for member utilities to host the mobile simulator. ■ *EPRI Contacts: Roy Fray, (415) 855-2441, and Ron Griebenow, (704) 875-5666*

Indoor Air Quality Info at Users' Fingertips

For electric utility personnel and others who need timely information on the concentrations of indoor pollutants (CIP), a comprehensive, easy-to-use database is now available that enables rapid searches of relevant literature. The CIP Database, which runs on IBM PC–compatible computers, provides information on indoor air quality issues and research drawn from peer-reviewed articles; government, EPRI, and National Technical Information Service reports; and conference proceedings.

Besides providing general information, the database guides the user in finding specific information through a series of search parameters. It allows a utility to obtain information on indoor air quality on the basis of building type and other factors in its service territory. A user's manual presents instructions for installing and using the database, as well as a tutorial to help the user become familiar with the procedures for conducting bibliographic and summary section searches. The current version of the CIP Database, 4.0 (order number SW-100533), is available through the Electric Power Software Center, (214) 655-8883. ■ *EPRI Contact: John Kesselring, (415) 855-2902*

New Calendar Makes Planning Easier for Members

For the first time in its history, EPRI is distributing a comprehensive calendar of its meetings and conferences to member utilities and other interested parties in the scientific community. The first issue of the Calendar of Events was released in November through EPRI's Technical Information Profile (TIP) System, which now has 18,000 subscribers.

The calendar will be issued quarterly and will provide an overview of meetings planned over a 12-month period. Explains Pam Turner, conferences supervisor at EPRI, the calendar "provides a tool that allows our member utilities to budget and plan in advance." It presents information on all kinds of EPRI events across the United States, including conferences, focus group meetings, workshops, and training courses sponsored by EPRI's many research centers.

The calendar offers a detailed list of events—arranged according to the sponsoring division within EPRI—that includes specific dates (when available) and contact names and phone numbers. It also gives a brief description of each division as an aid in locating meetings of interest.

The calendar is part of a broader initiative under way at EPRI to centralize information on EPRI events and to track more closely the attendance at meetings and workshops. As of November, all meeting information is gathered by EPRI's Corporate Communications Division, which has set up a database that other parts of the Institute can access. For instance, EPRINET, the Institute's electronic information and communications network, draws information for its on-line calendar of events from the Corporate Communications Division's database. (Since this on-line calendar also includes meetings that are planned within too short a time frame to make it into the listings distributed through TIP, EPRINET remains the best source for up-to-the-minute calendar information.)

The calendar presented in the *EPRI Journal* also will draw from the Corporate Communications Division's database but will continue to announce only major events. To subscribe to the EPRI Calendar of Events or to other publications distributed through the TIP System, contact Darlane Morgan at (415) 855-2859. ■

Video Introduces Magnetic Field Research Facility

EPRI has released an 11-minute video that introduces the Institute's state-of-the-art Magnetic Field Research Facility in Lenox, Massachusetts. This facility, the only one of its kind in the world, was established to provide a better understanding of the nature of residential magnetic field sources.

Operated by General Electric for EPRI and its members, the facility simulates a small segment of a residential neighborhood, including a 1200-foot overhead distribution line (with nine transformers) and an uninhabited house that draws power from the line. Within the house are typical wiring and grounding arrangements, which researchers can easily reconfigure to produce a wide variety of currents and magnetic fields typically found in residential neighborhoods.

EPRI uses the research facility to measure and evaluate magnetic fields and to

determine economical, practical ways to manage the fields. The Institute also encourages utility engineers to attend training courses at the facility to learn how to measure and analyze magnetic field data. Member utilities are invited to submit technical problems related to magnetic fields for further research. A number of outside groups have taken advantage of the expertise available at the facility; state health officials, appliance manufacturers, electric utility regulators, wire inspectors, foreign utility representatives, and U.S. Department of Energy personnel are among those who have visited the lab.

In addition to the facility, the new video describes a nationwide magnetic field measurement survey conducted by EPRI. This survey is the foundation for a comprehensive program that EPRI is developing to predict the strength of magnetic fields under a variety of residential wiring configurations. The video also covers methods of analyzing possible modifications to new and existing electric systems, discusses different options for magnetic field management, and cites specific EPRI tools available to help, such as Field Star™ 1000, a hand-held magnetic field measuring and recording device.

A member utility can order the video through its manager of EPRI technology transfer. ■

Combustion NO_x Control

Reburning for Cyclone Boiler Retrofit NO_x Control

by Angelos Kokkinos, Environment Division

Title IV of the 1990 Clean Air Act Amendments calls for a two-million-ton reduction in emissions of nitrogen oxides (NO_x), relative to 1980 levels, by a target date of 2000. A significant portion of this reduction will be accomplished by requiring fossil-fuel-fired power plants to meet more-stringent limitations on NO_x emissions. Compliance dates depend on boiler type, with cyclone boilers unaffected as yet but potentially subject to Phase 2 emission limitations beginning January 1, 2000. Moreover, under Title I of the 1990 amendments, boilers of any type (including cyclones) located in ozone nonattainment areas could be required to install NO_x controls by May 31, 1995.

Cyclone boilers are designed to reduce fuel preparation costs, minimize furnace size, and decrease the fly ash content of the flue gas. They burn crushed coal—typically smaller than 0.25 inch in diameter—and thus do not require pulverizers to prepare the coal for combustion. Combustion occurs within water-cooled horizontal cylinders, called cyclones, attached to the sides of the boiler. These cyclones are designed to create high-turbulence, high-temperature (3000–3400°F) combustion conditions sufficient to transform coal ash to molten slag, thereby reducing the fly ash content of the flue gas.

Cyclone boilers can be sized smaller than pulverized-coal-fired boilers with the same heat output, but they typically produce higher NO_x emissions. While cyclone boilers represent only about 9% of the coal-fired generating capacity built in the United States before the implementation of the 1971 New Source Performance Standards, they produce approximately 14% of the NO_x emissions from these pre-NSPS units. Staging the cyclone combustion process to reduce NO_x emissions is not a practical option, because this can change the physical and chemical properties of the ash—thus promoting boiler tube corrosion, altering slag flow characteristics, and leading to increased unburned carbon (UBC) levels and fly ash emissions.

Figure 1 is a sectional side view of a cyclone boiler modified for reburning operation. With reburning, 10–25% of the total heat input to the boiler is introduced through ports located above the cyclones to create a fuel-rich secondary combustion zone—the reburn zone. The reburn fuel does not burn in a well-defined flame but combusts uniformly throughout the reburn zone. Hydrocarbon radicals are formed as intermediate products in the process, and these radicals react with NO_x, chemically reducing it to molecular nitrogen.

To enhance the mixing of fuel and furnace gases and the reduction of NO_x without significantly increasing oxygen availability, recirculated flue gas can be added in the reburn zone. A third combustion area, known as the burnout zone, is created by injecting completion air above the reburn fuel ports. This step is necessary because oxygen levels in the reburn zone are purposely insufficient for complete combustion.

ABSTRACT *Reburning represents a promising retrofit combustion NO_x control technology for cyclone boilers. It involves the injection of natural gas, oil, or coal into the boiler above the main combustion zone in amounts equivalent to 10–25% of the total heat input. This creates a fuel-rich reburn zone in the middle region of the boiler in which NO_x is converted to environmentally benign molecular nitrogen. Two full-scale utility demonstrations—one using natural gas as the reburn fuel, the other using coal—indicate that NO_x emission reductions of about 40–60% are possible with minimal impacts on boiler operation.*

Demonstration program

Pilot- and full-scale tests cosponsored by EPRI indicate that reburning can reduce NO_x emissions by 40–60% without producing undesirable side effects, such as increased UBC and carbon monoxide (CO) levels. The technology is applicable only to units that are tall enough to provide sufficient time for both the reburn and final burnout processes to be completed (at least 1.5 seconds between the uppermost cyclone and the furnace outlet). An engineering feasibility study indicated that most cyclone boilers satisfy this criterion.

Pilot-scale tests using natural gas, oil, and pulverized coal as the reburn fuel were conducted on a 6-MBtu/h coal-fired cyclone boiler at Babcock & Wilcox Company's Alliance Research Center. NO_x emission reductions ranged from 40% to 75%. Reductions were highest when natural gas was used as the reburn fuel and lowest when coal was used. The effects of reburning on combustion efficiency and corrosion were insignificant with each of the three reburn fuels.

NO_x emission reductions in the 40–60% range have been achieved in EPRI-cosponsored full-scale reburning demonstrations at Ohio Edison's Niles Unit 1 and Wisconsin Power & Light's Nelson Dewey Unit 2. Natural gas was used as the reburn fuel in the recently completed two-year demonstration at Niles 1, a pressurized 110-MWe natural circulation reheat boiler burning an eastern bituminous coal. Pulverized coal is being used as the reburn fuel at Nelson Dewey 2, a 100-MWe pressurized boiler currently burning an Indiana bituminous (Lamar) coal. This demonstration is in its first year of operation.

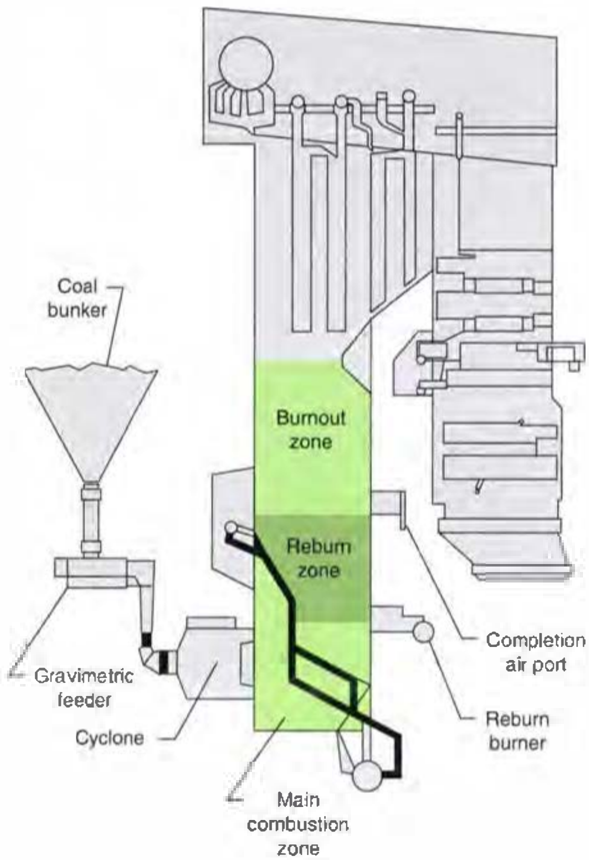
In general, the amount of NO_x destroyed by reburning depends on the following factors:

- The air-to-fuel ratio in the reburn zone. Results indicate that a stoichiometric ratio of 0.85–0.95 in the reburn zone optimizes NO_x reduction. (At this air-to-fuel ratio, the air is 85–95% of the amount needed for complete combustion of the fuel.)
- The type of reburn fuel. More-volatile, low-nitrogen-content fuels (oil and natural gas) reduce NO_x more effectively than less-volatile, higher-nitrogen fuels (coals).
- The length of time furnace gases remain in the reburn and burnout zones (residence time). Longer residence times allow complete mixing of furnace gases with the reburn fuel and the completion air. Minimum residence times are generally 0.5 second for the reburn zone and 0.6 second for the burnout zone.
- Temperature. NO_x reduction is maximized if the reburn zone temperature is as high as possible without hampering combustion in the primary zone, and if the burnout zone is as cold as possible without inhibiting carbon burnout.

Natural gas reburning at Niles 1

The natural gas reburning system at Niles 1 was installed in the spring of 1990. The system includes five reburn fuel ports and four burnout air ports. Key reburn zone components include a natural gas pipeline and associated control valves, a flue gas recirculation fan, ductwork and associated control dampers, and gas reburn nozzle assemblies. Key burnout zone components include ductwork, associated control dampers, and windbox and nozzle assemblies, through which completion air is injected into the furnace. Portions of the furnace waterwall have been replaced to accommodate the burners and air ports.

Figure 1 In a cyclone boiler modified for reburning, fuel equivalent to 10–25% of the total heat input is injected into a secondary combustion zone above the main zone. In this fuel-rich reburn zone, NO_x is chemically reduced to molecular nitrogen. Supplemental air is injected into a third zone, the burnout zone, to promote complete carbon combustion.



Operating procedures for the reburning system were developed during optimization testing in the summer and early fall of 1990. The system is operated in an automatic load-following mode by means of a programmable controller connected to the boiler's main control system. Final excess air levels are slightly higher than those for cyclone operation without reburning.

Short-term parametric tests were conducted during October–December 1990. These focused on assessing the effectiveness of the reburning system in reducing NO_x emissions, the impact of reburning system operation on boiler and plant operation and maintenance, and the influence of system variables and components on overall NO_x removal.

After the completion of the short-term parametric testing, long-term tests were conducted under typical load conditions, ranging from full load (110 MW) down to 80 MW. (Operating the reburning system at lower loads would have resulted in slag tapping problems.) The objective of these tests was to evaluate the effects of reburning on NO_x emissions and boiler performance under normal, everyday operating conditions.

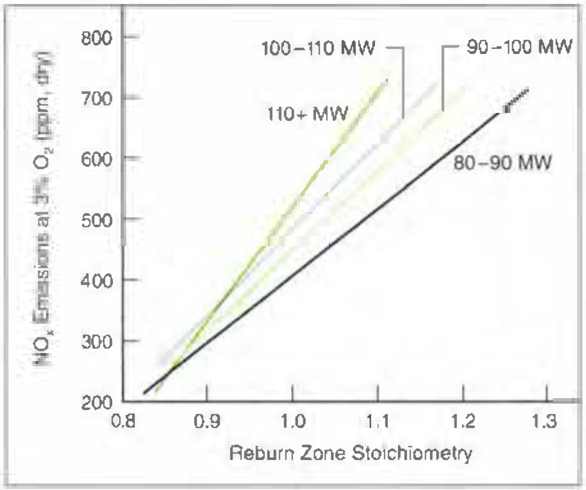
In the short-term parametric tests, the reburning system reduced NO_x emissions by 30–70% at both full and partial loads—from baseline levels ranging from 630 to 710 ppm. (All NO_x emission data are corrected to 3% oxygen.) In the long-term tests, NO_x reductions of 40–50% were achieved during normal boiler operation at a typical reburn zone stoichiometry of 0.9.

The impacts of the reburning system on both the boiler and the balance-of-plant equipment were generally minimal. However, overall boiler efficiency did decrease by approximately 0.7% as a result of the higher hydrogen content of natural gas, which increases flue gas moisture.

Waterwall heat absorption decreased by about 5% because of lower cyclone loading, but this was offset by a 5% increase in convective-pass heat absorption, the result of higher gas temperatures (about 30°F higher at the furnace outlet). Both UBC and CO levels were virtually unchanged. As would be expected as a result of burning natural gas in place of coal, sulfur dioxide emissions and particulate loading to the unit's electrostatic precipitator decreased.

The reburning system was initially designed with flue gas recirculation (FGR) to promote mixing of the natural gas reburn fuel with the furnace gases. However, the

Figure 2 Long-term test data on NO_x emissions versus the air-to-fuel ratio (stoichiometry) in the reburn zone at Niles 1. Increasing the flow of the natural gas reburn fuel at constant overall excess air levels (i.e., decreasing the stoichiometric ratio) lowered NO_x emissions under all load conditions tested. For a given increase in natural gas flow, the reduction in emissions was greatest at full load.



lower temperature of the recirculated flue gas reduced the temperature in the reburn zone, resulting in excessive slag deposits on the furnace walls. As a result, the reburning system was eventually redesigned to eliminate FGR.

Testing to assess the influence of system variables and components on NO_x reduction focused on reburn zone stoichiometry, FGR flow, completion air flow and delivery, and reburn fuel delivery.

As indicated by the long-term data in Figure 2, the amount of reburn fuel—and therefore reburn zone stoichiometry—has a strong, linear influence on emission performance at both full and partial loads. Stoichiometry was adjusted by varying the natural gas flow from 0% to 18% of total heat input. At constant excess air, a flow increase of about 9% corresponded to a 0.10 (10%) decrease in stoichiometry, which resulted in an NO_x emission reduction of approximately 200 ppm at full load. The data indicate that reburning is more cost-effective during full-load than partial-load operation; that is, a given increase in reburn fuel (and the associated decrease in stoichiometry) resulted in a larger NO_x reduction at full load (110+ MW) than at partial load (80–90 MW).

Varying FGR flow from 3% to 11% of total flue gas flow (design limits for mixing purposes) had no effect on NO_x emissions. This was due to the good mixing characteristics at Niles 1 and indicates that the influence of FGR on reburning system performance is likely to be unit-specific.

Varying completion air mass flow and delivery (e.g., varying the tilt and yaw angle of the four completion air injectors and biasing the flow to these injectors) had no effect on NO_x emission reduction. Varying the reburn fuel delivery parameters likewise had no effect on NO_x performance, but it did influence combustion completion and CO emissions.

Pulverized-coal reburning at Nelson Dewey 2

The pulverized-coal reburning system at Nelson Dewey 2 was installed in the fall of 1991. The system includes four reburn fuel ports and four burnout air ports. Key reburn zone components include a primary air fan, ductwork and associated dampers, a pulverizer and associated components, coal piping, a gravimetric feeder, coal-firing burners, and FGR ductwork and associated dampers. In addition, a silo for the reburn coal was installed. Key burnout zone components include air ports, ductwork, and associated dampers. New furnace wall panels were required to accommodate the burners and air ports.

As at Niles 1, the control system has been modified to include the control of reburn burners, FGR, and completion air flow. Parametric testing of the reburning system is under way; early results indicate that NO_x reductions will exceed the project goal of 50% with no significant operating impacts.

State-of-the-Art Power Plant

Fossil Plants: Integrating New Technology and Design

by Stan Pace, Generation & Storage Division

During the recent hiatus in new power plant construction in the United States, research by EPRI and domestic and overseas manufacturers has produced major advances in fossil fuel plant technology and design. Anticipating utilities' need for timely information on these advances, EPRI initiated a project to define state-of-the-art power plant (SOAPP) designs and to transfer SOAPP technology and cost data to the industry (RP3222-1). The project is developing a comprehensive computer-based information system for integrating proven fossil plant equipment technology into new units and retrofit projects.

The project will cover pulverized-coal, combustion turbine, combined-cycle, circulating-fluidized-bed combustion, and gasification–combined-cycle systems. The initial work is focusing on combustion turbine and combined-cycle plants and on environmental technologies for pulverized-coal plants.

The SOAPP information system consists of two key elements: technology modules and the SOAPP workstation. A technology module is a stand-alone information software product that serves not only as an immediate technology transfer tool but also as a building block for the SOAPP workstation. The project staff plans to develop as many as 120 technology modules.

The SOAPP workstation provides integrated access to the technology modules.

ABSTRACT *In a power generation market characterized by increasing competition, utilities need to effectively apply cost-beneficial advances in fossil plant technology and design that have come out of research sponsored by EPRI and other organizations around the world. To support utilities in this effort, EPRI is developing a powerful computer-based information resource consisting of an easy-to-use design and analysis workstation and a comprehensive set of technology modules. This system not only will provide detailed information on proven innovations for fossil plants but will help utilities integrate these state-of-the-art technologies into new plants and retrofit applications.*

Using this single workstation, utilities will be able to screen fossil generation technologies on the basis of their own project goals and to evaluate alternative technology strategies for various plant sizes, fuels, and site requirements. They will also be able to develop customized SOAPP conceptual plant designs and conduct cost and performance sensitivity analyses. Through this process, utilities can plan for totally integrated SOAPP facilities that they can confidently specify, design, build, and operate—thereby taking full advantage of the technological advances now available.

A computer-based information resource

The primary purpose of the SOAPP project is to provide a comprehensive, user-friendly information system to help utilities design new and retrofit plants that offer increased efficiency, availability, environmental compatibility, and cost-competitiveness. Technologies are selected for treatment in the SOAPP technology modules primarily on the basis of their potential for contributing to these plant improvement goals.

Each technology module will contain the following: a process description (including diagrams and a discussion of advantages and disadvantages), design-basis information, information on economics (including a detailed cost breakdown), scheduling information, a discussion of new versus retrofit issues, a database on operating experience with the technology, a list of references, and a glossary. Screening modules will provide fast access to all the technology modules and will perform basic screening of these technologies in terms of applicability to a given site.

Table 1 lists the project's first 19 technology modules. Three of these modules—electrostatic precipitators, baghouses, and cycle chemistry—are complete; the remaining 16 will be released for beta testing by the end of 1992 and will be available in early 1993. Later next year, 16 additional technology modules will be completed, along with the combustion turbine/combined-cycle portion of the workstation.

For each type of fossil generation covered in the workstation, the project team is developing a base case SOAPP conceptual design as well as associated capital and operating cost estimates. These base case designs will integrate many of the advances described in the technology modules and are intended to "push the envelope" of plant performance, costs, and environmental compatibility. A utility can use a conceptual design as the starting point for a customized design, selecting whatever technologies are consistent with its goals and constraints.

In addition to integrating appropriate technologies, the base case SOAPP conceptual designs will include advanced construction techniques—for example, preassembly, ground assembly, and modular construction. By making extensive use of these techniques, the base case conceptual designs will facilitate plant construction, lower costs, and shorten schedules.

The SOAPP workstation will enable users to input site-specific criteria, select any combination of plant equipment, and view the effects on plant design, layout, cost, and performance. Users will be able to vary key design criteria—including plant size, steam conditions, duty cycle, fuel type, and emission limits—and assess the impacts on the conceptual design. Changes that workstation users make in the plant design criteria and in their technology selections will automatically be propagated throughout the drawings, cost estimates, and other conceptual design documentation.

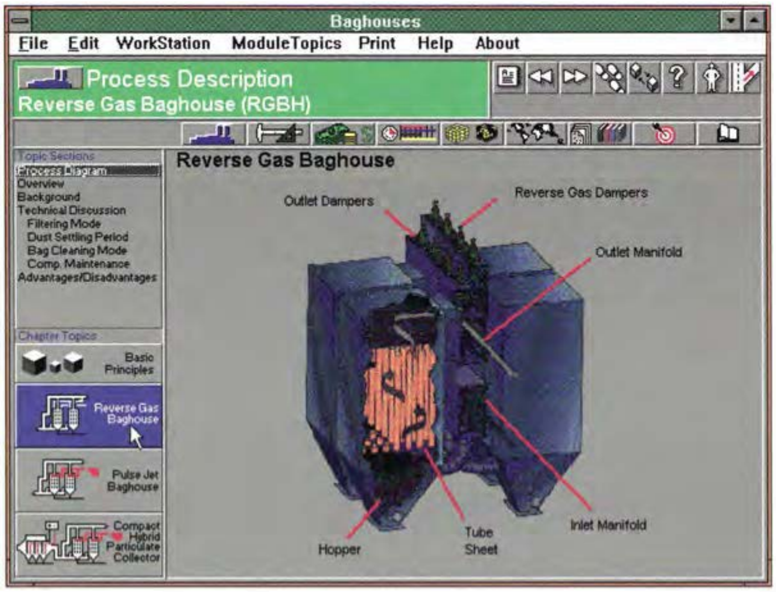
Innovative technology transfer

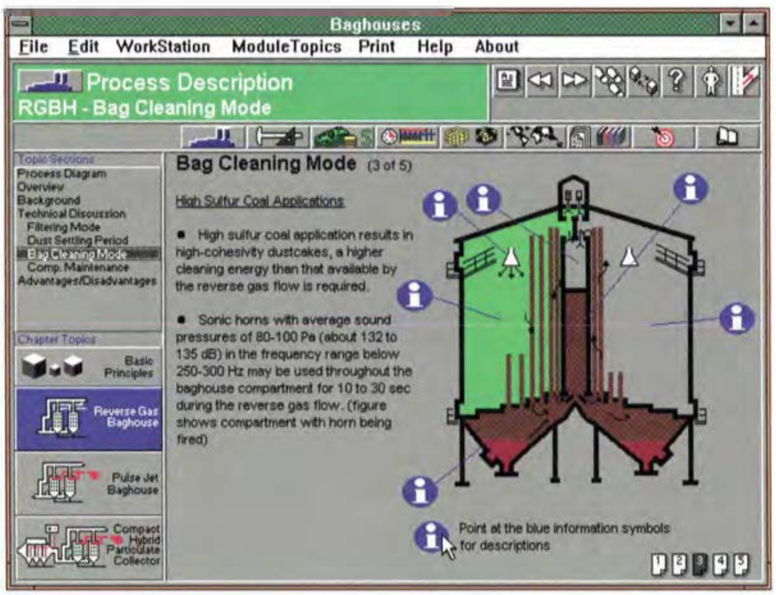
The key to the technology transfer aspect of the SOAPP project is the application of innovative software technologies and a sophisticated but very friendly graphic user in-

Table 1
INITIAL SOAPP TECHNOLOGY MODULES

Electrostatic precipitators*
Baghouses*
Cycle chemistry*
Flue gas desulfurization (FGD) selection
Forced-oxidation lime/limestone FGD
Inhibited-oxidation FGD
Dry FGD
Continuous emissions monitoring
Pulverized-coal postcombustion NO_x control
Coal cleaning
Coal switching and blending
Pulverized-coal burners
Steam bypass systems
Feedwater heaters
Feedwater pumps
Air heaters
Combustion turbine selection
Combustion turbine combustor NO_x control strategies
Combustion turbine postcombustion NO_x control

*Available now.





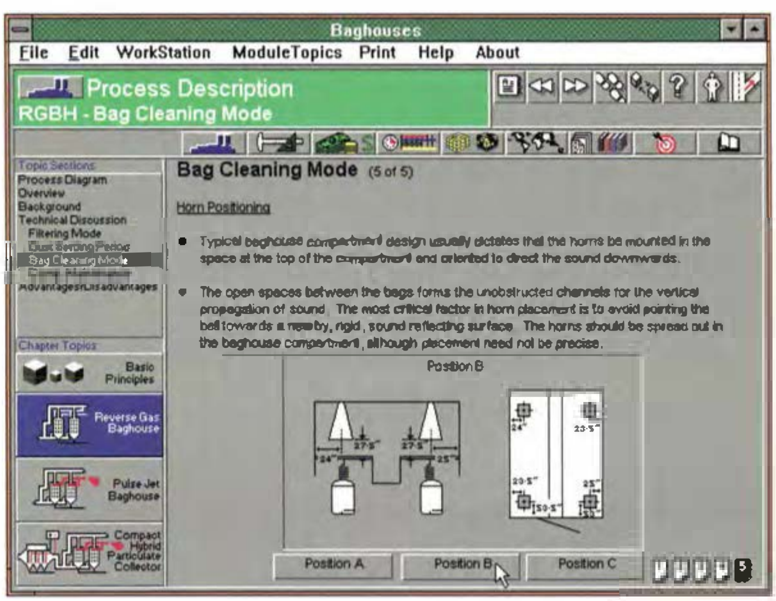


Figure 1 Designed to take full advantage of the computer medium, the SOAPP technology modules feature sophisticated yet user-friendly displays that present three levels of technical information. At the first level, a graphic illustration gives an overview of the topic—here, for example, reverse gas baghouses (top). Through icons, hypertext technology, and other on-screen navigational tools, users can easily access more-detailed information like that shown on the other screens.

terface. An important concept in the development of the SOAPP technology modules and workstation is *information visualization*, an approach that goes beyond the straightforward conversion of paper documents to electronic media (although that is part of the SOAPP effort) to include information design.

This approach is based on the realization that significant gains in productivity can be achieved by designing information to take full advantage of the computer medium. It features a standardized format for user access, the use of visual aids and interactive displays, and the extensive cross-linking of information to create hypertext/hypermedia and multimedia (i.e., audio and video) support. As a result of the system's innovative design, a broad range of utility users will—with minimal training—be able to access a great variety and depth of information. Users will literally have at their fingertips the essence of hundreds of volumes of published information.

In the technology modules, technical information is presented at three levels, with summary graphics at the first level and more-detailed information at the second and third levels (Figure 1). This arrangement allows users to obtain a quick overview of a major area (e.g., process description, economics, scheduling), after which they can selectively access more-detailed information. In the workstation, a similar approach allows users to select various design criteria and parameters in order to develop customized plant designs.

Time-sensitive information—such as information on costs, equipment delivery schedules, and operating experience—is stored in calculation libraries and databases used by the SOAPP workstation. These libraries and databases will be updated regularly and made instantaneously available to workstation users over a wide-area network, EPRI's PowerServe.

Benefits to utilities

In the SOAPP project, innovative software technologies are being used to create a powerful workstation that can help utilities understand the impacts of available technology improvements for existing and new fossil plants. The workstation will screen technologies to identify candidates appropriate for a given site; provide guidelines on as many as 120 technologies; and supply drawings, equipment lists, energy and material balances, cost estimates, and schedules for site- and utility-specific versions of the SOAPP base case designs.

In addition to making possible comprehensive technology evaluations, the workstation will offer utilities the following important benefits:

▫ Readily available technical information. Utilities continually seek ways to improve the availability and accuracy of data on generation performance, cost, efficiency, and scheduling for their planning studies. The SOAPP workstation will provide this information quickly and economically. It will also provide related design information that will enhance reports and studies.

▫ Reduced need for external support. Most utilities strive to achieve self-sufficiency without sacrificing quality and timeliness. The SOAPP workstation will give utilities the capability to internally generate conceptual information about fossil power plants.

▫ Economical investigation of what-if scenarios. Utilities will no longer have to oversimplify screening studies that determine the impacts of such attributes as unit size, fuel quality, and emission limits. The SOAPP workstation will make it possible for utilities to perform detailed sensitivity analyses and what-if scenarios quickly and cost-effectively.

The SOAPP software is designed not only for utility system planners but also for utility engineers and managers. A utility engineer might use it to develop conceptual designs, information for siting studies, technical data for licensing and permitting activities, or technical input for generation planning. A utility manager might use the software to access design data and other critical information for submission to regulatory and licensing agencies or for use in presentations to company management.

The SOAPP goals will be met only if utilities understand the how and why of integrating the latest technologies into power plants. The state-of-the-art software technology and information visualization techniques employed in the SOAPP workstation and technology modules should give utilities the necessary knowledge and confidence to optimize conceptual designs for reliable, competitive power generation facilities for the future.

The project team

A multidisciplinary contractor team, led by Sargent & Lundy Engineers, is developing the SOAPP workstation. Data for the individual technology modules are being collected and developed by a group of subcontractors selected for their expertise in specific technical areas. The team also includes 11 host utilities, who not only provide guidance on workstation development but also take an active part in it. A project advisory committee with representatives of 24 utilities and 12 architect/engineering and equipment supplier firms has been formed and meets regularly.

To ensure the SOAPP project's responsiveness and usefulness to members, EPRI continues to invite utility participation in advisory committee, users group, and site study activities. For more information on the project, contact Stan Pace at EPRI, (415) 855-2693. For a demonstration disk of the SOAPP software, contact the EPRI Distribution Center, (510) 934-4212.

DSM and Residential Programs

Impacts of Appliance Efficiency Standards

by Phil Hummel and John Kesselring, Customer Systems Division

Improvements in design, materials, components, and manufacturing methods have yielded impressive efficiency gains for home appliances, which currently account for about 20% of U.S. electricity demand. These improvements—together with federal minimum efficiency standards, which eliminate low-efficiency models from the market—have significantly altered the spectrum of appliance efficiency options available to consumers and, in turn, the options open to utilities interested in demand-side management (DSM).

Federal regulation of the energy efficiency of appliances began in 1987 with the enactment of the National Appliance Energy Conservation Act. The NAECA, which has been amended several times, specifies efficiency standards for 13 classes of home appliances (Table 1). Each standard is intended to achieve the maximum improvement in energy use that the Department of Energy determines to be technologically feasible and economically justified. In setting a standard, DOE is to consider several factors, including the results of product performance testing; the economic impact on manufacturers; consumer savings in energy costs throughout the product life; increases in price or maintenance costs; and the total energy savings likely to result from imposition of the standard.

EPRI's Residential Program is working with manufacturers to develop electric appliances with efficiencies that exceed existing and proposed standards. Such appliances could lead to the adoption of even higher standards. For instance, the microwave clothes dryer being developed by EPRI could prove efficient enough to push up standards for clothes dryers, and EPRI-sponsored work on heat pump water

ABSTRACT *Federal efficiency standards for appliances limit the range of models available on the market. Utility energy efficiency programs often encourage consumers to purchase the most efficient of the remaining options, but more-stringent efficiency standards could have a significant impact on such utility efforts. Using long-run technology scenario forecasting, EPRI-sponsored researchers studied ways in which the interplay of technological change, federal standards, utility efficiency programs, and market forces could affect future energy markets for three major residential end uses: refrigeration, central air conditioning, and water heating. The researchers reached several important conclusions about utility demand-side management efforts.*

heaters could help raise standards for water heaters.

In connection with integrated resource planning, many utilities are evaluating their DSM options. As federal efficiency standards narrow the range of available appliance options, utility DSM planners must consider the costs and benefits of offering incentives for consumers to purchase the most efficient of the remaining options. EPRI's DSM Program is examining the potential impact of appliance efficiency standards on future load and on utility DSM efforts.

Technology scenario forecasting

Technological changes, efficiency standards, and market forces will mold future residential appliance energy markets. Long-run technology scenarios provide a structured framework for studying these influences and the limits they place on DSM potential. The scenarios take into account new equipment designs, restrictions imposed by efficiency standards, and incentives provided by DSM programs. They also examine interactions between end uses, especially the relationship between improved appliance efficiency and heating and cooling loads.

Under EPRI contract, Regional Economic Research, Inc. (RER), used long-run technology forecasting techniques to analyze the potential impact of appliance efficiency standards on energy consumption and on utility DSM efforts. As a support tool, RER used EPRI's REEPS 2.0, the Residential End-Use Energy Planning System, a software package for developing end-use energy forecasts. REEPS combines end-use and technology data with key assumptions about dynamic market behavior to develop information on energy sales, fuel and technology market shares, and appliance size, efficiency, and use.

To construct long-run technology scenarios, analysts had to make explicit assumptions about the development and introduction of advanced technology and about changes in efficiency standards. Owing to the complexity of the situation being studied, they made certain simplifying assumptions. For instance, since the number of specific appliance options available on the market is too large to be modeled in detail, the researchers grouped models into representative design sets that together covered the full efficiency spectrum over the forecasting period. Then, taking into account scheduled and anticipated minimum efficiency standards, the researchers determined the

Table 1
SCHEDULE FOR FEDERAL APPLIANCE EFFICIENCY STANDARDS

Appliance Class	1988	1990	1991	1992	1993	1994	1996
Clothes washers	●					●	■
Clothes dryers	●					●	■
Dishwashers	●					●	
Refrigerators, refrigerator-freezers, freezers		●			●		
Water heaters		●	●				■
Direct heating equipment		●					■
Kitchen ranges and ovens		●					■
Pool heaters		●					■
Room air conditioners		●					■
Central air conditioners and heat pumps							
Split system				●			
Single package					●		
Furnaces							
Central (>45,000 Btu/h)				●			
Small (<45,000 Btu/h)				●			
Mobile home		●					■
Boilers				●			
Fluorescent lamp ballasts		●					■
Televisions							■

Note: A bullet indicates the effective date of a current standard or of a future standard whose value has already been set. A square indicates the scheduled date for a new or updated standard whose value is yet to be set.

least- and most-efficient options available on the market during any given year in a scenario. They also identified potential DSM targets—models typically in the upper portion of the efficiency range (Figure 1). The minimum level of appliance efficiency targeted by DSM programs will change over time, especially as future standards narrow the range of available options.

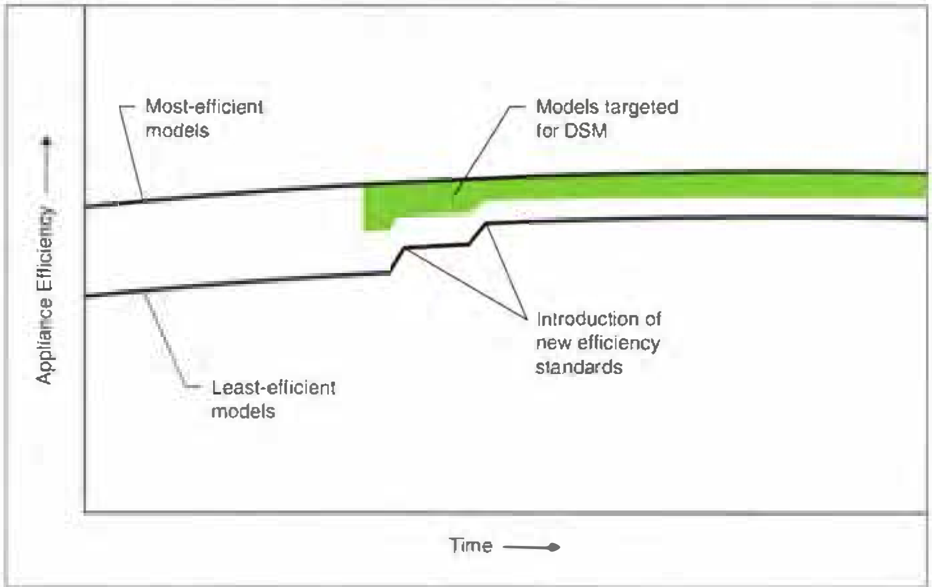
Efficiency standards have an impact on energy use only as new and replacement appliances are purchased. The average efficiency of new appliances purchased during any year reflects the overall efficiency range of the appliance options in that year, the availability of the various options, the marketing strategies of suppliers, and the decisions of home builders and consumers. A change in the average efficiency of the existing stock of residential appliances occurs gradually, because the average efficiency at any point in time reflects appliance technologies and purchase decisions from the preceding decades. However, as low-efficiency units are removed from service and from the market and as more-efficient models are purchased, the average efficiency of the existing stock will rise, and energy consumption per unit will fall, unless there are offsetting trends like increases in appliance size and usage levels.

To evaluate the implications of efficiency improvements for utility sales and for potential DSM programs, the analysts considered several other factors, including the thermal efficiency of homes and the application of add-on measures (e.g., low-water-flow devices) that do not involve major equipment expenditures but are often covered by DSM programs. Finally, they considered several interrelationships between efficiency and consumption, including equipment-related internal heat gains (i.e., appliance-generated heat and its effect on heating and cooling loads) and interactions between usage and behavior (e.g., the rebound effect, or the customer's investment of efficiency savings in increased energy consumption).

Three end-use analyses

RER recently completed analyses of the interplay of appliance efficiency standards, DSM programs, and market forces for three types of residential appliance: refrigerators, central air conditioners, and water heaters.

Figure 1 Framework for technology scenarios. The top curve represents the most efficient of the models on the market in a given appliance class; the bottom curve, the least efficient. Utility DSM programs encourage consumers to purchase models in the upper part of the available efficiency range, taking into account local economics and buying patterns. When new efficiency standards are introduced, low-efficiency models are forced off the market and DSM targets move upward.



Refrigerator efficiencies have risen dramatically over the past decade, and new units purchased in the next few years will strongly outperform most units in the existing stock. During the early 1990s, the influence of DSM efficiency incentives on new refrigerator purchases will be limited by the narrow and rapidly upward shifting efficiency range defined by available model options.

The efficiency of refrigerators is expressed in terms of an energy factor that indicates the number of cubic feet refrigerated under test conditions by 1 kWh per day. According to manufacturers' shipment data, energy factors for new units ranged from 8 to 9 in 1991. The more stringent standard to take effect in 1993 will force the minimum efficiency level to an energy factor of about 11, to be met through increased insulation and compressor efficiencies. (Standards are specified according to the size and features of the appliance. The energy factor of 11 is for a typical, frost-free 18-cubic-foot model that has a top-mounted freezer and no through-the-door features.)

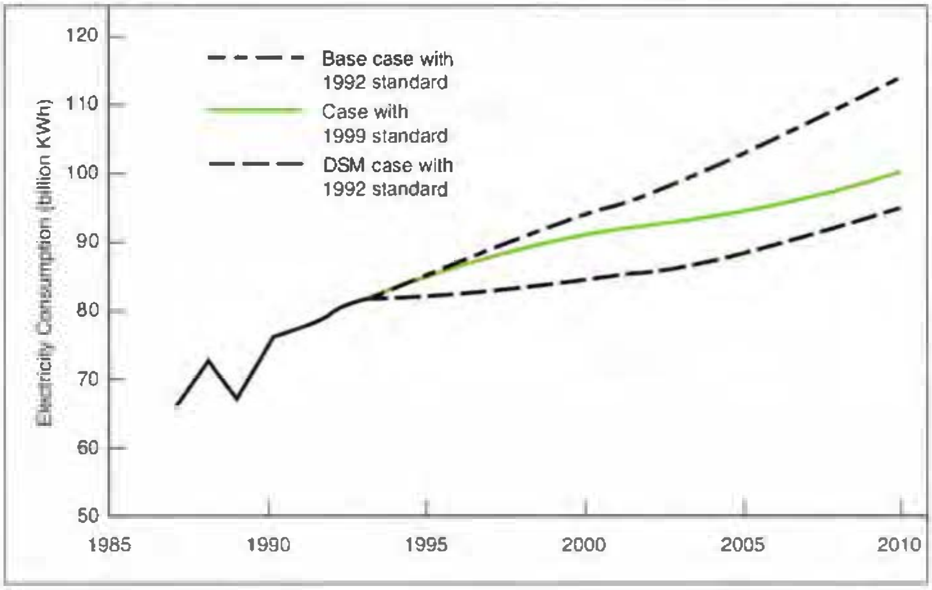
Once the 1993 standard is in place, DSM programs aimed at the early replacement of existing units can be expected to result in some short-term energy savings. Also, DSM second-refrigerator buyback programs (i.e., programs whereby utilities purchase from consumers inefficient units being used as second, auxiliary refrigerators) will remain a source of energy savings. Beyond these, the nature of DSM refrigerator programs will largely depend on further technology development.

EPRI's Commercial and Residential programs are jointly investigating the development and application of new refrigerants having zero ozone-depletion potential. If such refrigerants prove feasible, they may have an impact on refrigeration system efficiencies, but it is too early to determine how such an impact would affect refrigerator efficiency standards.

The RER researchers did construct a scenario to examine another potential development in refrigeration technology—the use of vacuum panels instead of insulation. The scenario assumes that refrigerators using these panels and operating with an energy factor of 15 will become commercially available in the late 1990s. With no further tightening of national standards and without aggressive DSM activity, the market share of these units is expected to be low.

Overall, the REEPS national database forecasts a sharp decline in first-refrigerator

Figure 2 Scenarios for forecasting central air conditioning electricity consumption. Both the base case and the DSM scenario are based on the 1992 federal efficiency standard. The analysis indicates that by the year 2010, utility DSM efforts could reduce electricity consumption by 19 billion kWh from the base case. The introduction of a more stringent standard in 1999 would itself result in a large decrease in consumption, however, and hence limit the potential of DSM efforts.



energy consumption, from about 1250 kWh per unit per year in 1990 to about 720 kWh in 2010. Despite a 22% increase in the number of households, the forecast calls for a 30% decline in refrigerator energy use in the residential sector nationally. This decline is attributed mainly to the stringent 1993 national efficiency standard. The associated loss of internal heat gain from refrigerators will add almost 8 billion kWh to electric heating loads by 2010 but will reduce electric cooling loads by more than 3 billion kWh. As a result, each 100 kWh in refrigerator energy savings will be offset in part by a load increase of about 8 kWh. The loss of refrigerator heat will also increase the use of natural gas and other fossil fuels for heating by 3.5% in 2010.

The efficiency of central air conditioners, like that of refrigerators, has increased significantly over the last 20 years. However, current federal standards do not approach the upper part of the available efficiency range, as they do for refrigerators, largely because more-efficient air conditioning units include relatively expensive components, such as variable-speed motors. Given the large gap between the seasonal energy efficiency ratio (SEER) of available high-efficiency air conditioning units (>16 Btu/Wh) and the 1992 federal standard (10 Btu/Wh), there are options within the existing efficiency range for DSM programs to target. Also, the market is first-cost sensitive. Thus, depending on local economics and usage patterns, there is potential to significantly reduce the amount of energy consumed for residential air conditioning.

As shown in Figure 2, a base case scenario using the 1992 standard projects that electricity consumption for central air conditioning will grow from about 80 billion kWh in 1992 to more than 110 billion kWh by 2010, reflecting the growth in housing stock, the use of central air conditioning in most new homes, and the installation of new units in existing homes. According to a DSM scenario also based on the 1992 standard, utility programs to encourage the purchase of more-efficient units could reduce energy consumption for air conditioning by 17%. Such programs could prove especially successful in warm climates, where the heavy use of air conditioners would quicken payback on consumer investment. On the other hand, if a standard at a SEER level of 12 Btu/Wh were imposed in 1999 as a result of improvements in compressor efficiency or other advances, the potential impact of DSM programs in the year 2010 could be greatly reduced.

Improvements in residential building thermal efficiency prolong cooling effects and so normally lower air conditioning use. The thermal efficiency of homes is expected to improve by about 5% over the next 20 years without DSM programs and national standards. Any additional improvement will reduce the incremental value of more-stringent efficiency standards for air conditioners and of DSM efforts to promote high-efficiency models. Further, many DSM programs that help increase average appliance efficiencies will also lower internal heat gains from appliances, thus lowering cooling loads and reducing potential savings from increases in cooling-equipment efficiency.

The third end use analyzed by RER was water heating. The efficiency of electric resistance water heaters is close to technical limits, and—unlike refrigerators and central air conditioners—they have limited potential for efficiency improvement. (Heat pump water heaters have potential for dramatic efficiency improvement over electric resistance units; efforts to improve their cost-effectiveness are continuing.) In essence, standards imposed in 1990 took electric resistance water heaters with relatively inadequate insulation off the market, thus narrowing the available efficiency range and limiting the role of DSM programs that involve the purchase of resistance units.

However, utilities do promote add-on measures that can still provide large water-heating energy savings. For instance, although water heater jackets are a poor investment for owners of high-efficiency water heaters, the use of such jackets on less-efficient units provides quick payback to consumers and could result in energy savings of 4 billion kWh a year in 2010, even if a more stringent efficiency standard is introduced in 1996. Other effective add-on measures include the use of heat traps to reduce standby losses (by minimizing the mixing of water in pipes with water in the tank) and the use of low-flow shower heads and water aerators to reduce hot water flow. Utilities can also help cut water-heating energy use by encouraging consumers to buy water-efficient clothes washers and dishwashers and to reduce temperatures in user-controlled water heaters.

In summary, the RER analyses indicate that new federal efficiency standards for appliances will have an important impact on electricity demand. By 2010, for example, increased refrigerator efficiency is expected to reduce residential electricity consumption by 3%. New standards will also strongly affect utility DSM programs. Utilities therefore need to evaluate their DSM programs constantly, especially when new efficiency standards are announced or take effect. EPRI will continue to apply technology scenario forecasting techniques and will use the results to update databases for energy forecasting tools and to revise such publications as *Impact of Demand-Side Management on Future Customer Electricity Demand* (CU-6953). For more information about long-run technology scenario forecasting or REEPS, contact Phil Hummel at (415) 855-2855. For information about residential appliance technology, contact John Kesselring at (415) 855-2902.

Artificial Intelligence

Exploring Neural Network Technology

by Joseph Naser, Nuclear Power Division, and John Maulbetsch, Office of Exploratory & Applied Research

Neural networks—an emerging artificial intelligence technology—consist of a number of simple, highly interconnected data-processing units that some believe may approximate the complex system of neurons and electrochemical signals used by the human brain to process information. There are structural similarities between artificial neural networks and biological neurons (Figure 1), and neural networks can successfully accomplish tasks that are routine for humans but extremely difficult for conventional computer software systems. These tasks include recognizing patterns, forming associations, making generalizations, and learning from experience.

Neural network technology is already being used in such varied areas as explosives detection, process control, underwater object identification, and loan approval evaluation. Large-scale utility applications of neural networks require a thorough understanding of their nature, capabilities, and design.

In EPRI-sponsored investigations, researchers are examining neural network characteristics and evaluating such applications as control of power systems and combustion processes, diagnosis of check valve operating conditions, and recognition and digitalization of hand-lettered text in engineering drawings. Results to date illustrate the potential of neural networks for improving these and other complex utility operations.

ABSTRACT *EPRI is funding several projects to explore neural network technology, a form of artificial intelligence that some believe may mimic the way the human brain processes information. This research seeks to provide a better understanding of fundamental neural network characteristics and to identify promising utility industry applications. Results to date indicate that the unique attributes of neural networks could lead to improved monitoring, diagnostic, and control capabilities for a variety of complex utility operations.*

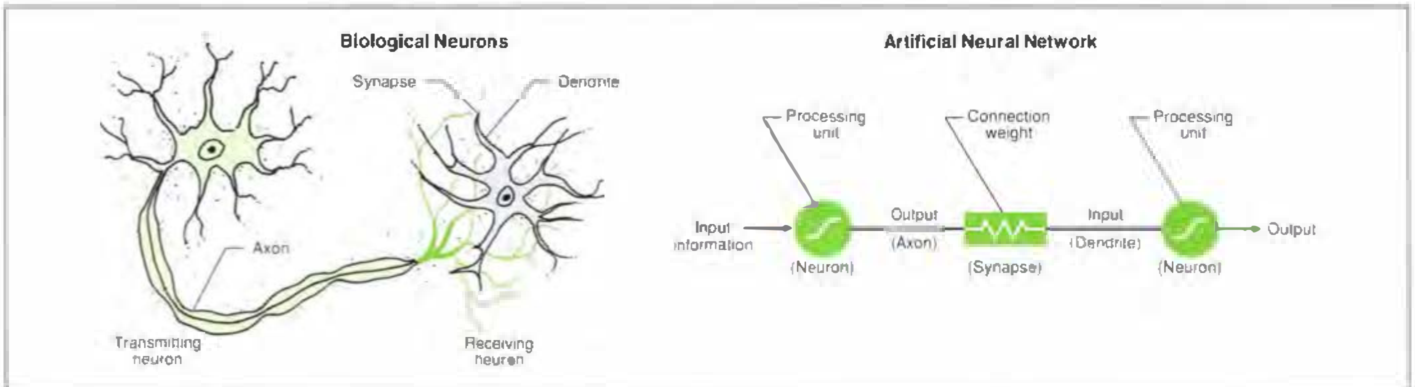
Characteristics and structure

The most important characteristic of neural networks is their ability to learn and adapt. Conventional software systems are programmed with instructions and rules, whereas neural networks define, or learn, their own rules on the basis of examples ("training" data). Although various training approaches exist, the process generally involves feeding data into a network and then iteratively adjusting the network's internal parameters to enable it to develop relationships between data and to model the process that produces the data. Once properly trained, neural networks can perform the same tasks on data other than the training set and have the potential to adapt to changing conditions through a continuous self-optimization process.

Other important attributes include robustness and parallelism. Neural networks are more robust than conventional computer programs in their ability to handle noisy or missing data or damage to components. As a result, their performance degrades gradually as data quality decreases or damage increases, instead of catastrophically failing. Parallelism provides the ability to perform many operations at once, which is necessary for some real-time or data-intensive applications. It also enables a network to consider many possible solutions to a problem simultaneously, whereas conventional software can evaluate only one option at a time. These advantages are attributable primarily to the structure and distributed functions of neural networks.

Neural nets consist of two basic elements: processing units, which are arranged in layers, and connections between units, which are of variable weight, or relative influence. Unlike conventional computer techniques, which process information serially, neural nets process information in a distributed way in a pattern of activation that spreads,

Figure 1 In biological neural systems (left), electrochemical signals travel from a transmitting neuron's axon across a tiny gap to a receiving neuron's dendrite. This gap, called a synapse, influences the receiving neuron's response to the signal. In artificial neural networks (right), information is processed in a loosely analogous way. Signals pass between processing units (neurons) through connections (axons, dendrites); connection weights (synapses) determine the effect of an input signal on the next processing unit.



unit by unit, throughout the network.

Each processor performs a single, simple operation on the information it receives from input data or other units. Results are then included as part of the network's output or are transmitted as signals to other units for additional processing. Interconnection weights—which networks establish during training and adjust in response to changing data conditions—can increase or decrease signal strength, thereby influencing the way other units process information. The memory of neural nets is distributed within these weights rather than stored in specific areas, as in serial computers.

Network architecture—the number of layers, the number of processing units in each layer, and the number of interconnections—can be customized for specific applications. Typical networks have three layers: one to receive input, one to transmit output, and a third, "hidden" layer (Figure 2). Units in hidden layers are not directly involved with input or output but instead help transform input to produce output. They enable networks to form representations, or models, of the outside world that can be used to make complex decisions.

EPRI projects

Two projects sponsored by EPRI's Office of Exploratory & Applied Research are focusing on the ability of neural networks to optimize the control of processes that are unstable, nonlinear, or not fully understood. Existing control techniques, such as classical adaptive filters, are able to handle only small, linear changes in process conditions. Because of their learning abilities and adaptive nature, neural networks can control processes with large, unpredictable variations.

Two other projects are exploring the technology's ability to recognize patterns. Neural nets excel at pattern recognition because they can identify objects that are similar but not identical, extrapolate missing information, and deduce patterns from noisy data.

A fifth project is examining a novel design that relates a network's architecture to the operations it is intended to perform. Currently, the development and training of networks with appropriate architectures for specific applications is one of the major challenges to widespread use of this technology.

Control system research

Researchers at Stanford University are studying the application of neural network technology to the control of power systems that exhibit complex, nonlinear behavior (RP8010-13). Initially, to establish the feasibility of this approach, a neural network controller was designed and trained for a simple single-generator/single-load system. The controller maintained output voltage during random load changes with rapid response time and minimal signal distortion.

Recent work has focused on the development of a neural network load-frequency controller (LFC) for a more complex system. Most LFCs use integral controllers to eliminate generator frequency transients as rapidly as possible following load perturbations. To minimize overshooting, these controllers do not respond until transients reach a certain magnitude, and therefore they are somewhat slow. In addition, they cannot account for possible nonlinearities in the generator response.

By receiving an estimate of the load perturbation as an input variable, the neural network LFC avoids the need to compromise between transient recovery and overshooting. The network controller can immediately counteract the effect of the perturbation and achieve rapid transient recovery. It is also capable of dealing with nonlinearities. Researchers plan to test the neural network LFC on increasingly complex and realistic models and, eventually, actual power systems.

Scientists at Physical Sciences, Inc., in Andover, Massachusetts, are investigating neural network–based control of fossil fuel burners (RP8005-13). A simple experimental combustor has been developed in which the flame state is entirely dependent on the airflow rate. Imaging equipment is used to capture the flame's flow structure by monitoring the chemiluminescence of the hydroxyl radical within the flame. Each image, divided into 1024 pixels, is fed into a three-layer neural network with 1024 input nodes.

The network classifies images into 10 flame energy release states, ranging from "sputter out" to "blowoff." Network output is communicated to an integrated controller that adjusts airflow to maintain a desired state under various extraneous perturbations. Follow-on work is evaluating the neural network–based controller's ability to minimize the production of nitrogen oxides in a variable-geometry, swirl-stabilized laboratory-scale combustor.

Pattern recognition

Researchers at the University of Tennessee are investigating the applicability of neural networks for real-time monitoring of check valve performance (RP8010-12). Such monitoring is important, since check valve failures in nuclear power plants may compromise plant availability and integrity. Existing methods of inspecting valves for physical damage, however, require specialized expertise and are labor-intensive and expensive. The aim of this project is to develop an on-line inspection method that uses a neural network trained to identify acoustic emission signatures characteristic of normal check valve operation, as well as signatures indicating specific physical problems.

A network has been trained by using input and output data collected from check valve hinge pins and backstops, respectively. In trouble-free valves, these data sets differ slightly but in a known manner. The network accurately predicts the backstop signal for properly operating valves. Predictions are less accurate for malfunctioning valves, and the magnitude of error varies for identical valves with differing problems. These results indicate that neural networks can identify trouble-free and malfunctioning valves and may be able to diagnose specific problems. At present, researchers are attempting to optimize network performance and diagnostic capabilities by using additional valve data and various architecture and training approaches.

Scientists at Kaman Sciences Corporation (Syracuse, New York) and a group of universities are exploring the use of neural networks and other technologies to improve the state of the art in the recognition, capture, and verification of hand-lettered text (RP8010-16). Before the advent of computer-aided design systems, utility engineering drawings were produced in hand-drawn paper format. Paper-based drawings contain a wealth of information necessary for plant design, construction, operation, and maintenance activities, but they are difficult to access, update, and use.

Existing methods of transforming these drawings into computer format are labor-intensive or inaccurate. The goal of this project is to develop a faster, more accurate method, and initial results show promise. Experience gained in this effort is expected to be incorporated into a project sponsored by EPRI's Nuclear Power Division (RP3045-1) to automate computer digitalization of

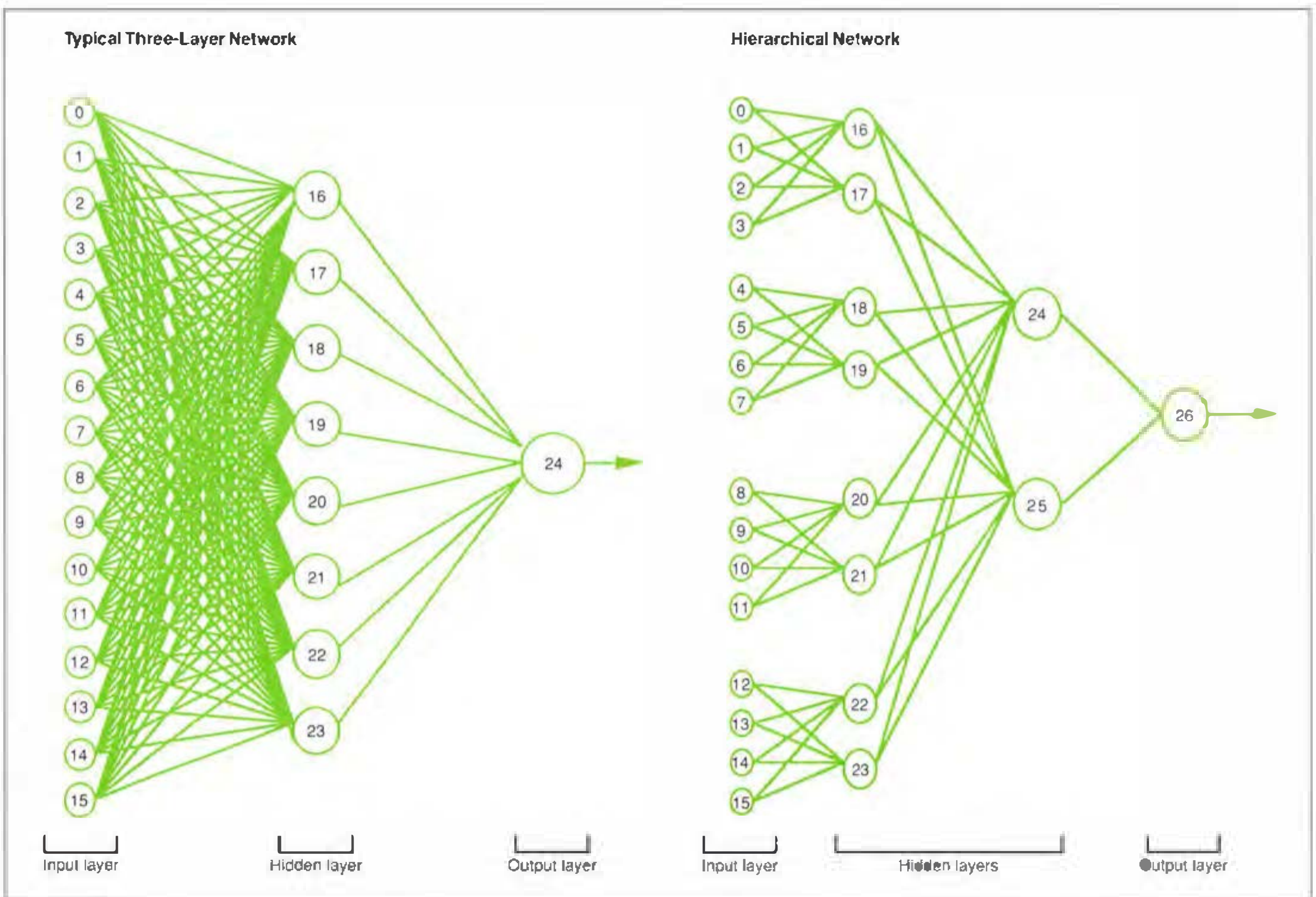


Figure 2 Neural networks have multiple layers of processing units—one layer to receive input, one to transmit output, and one or more "hidden" layers used in developing a model of the system or process being analyzed. In typical three-layer networks (e.g., the simplified network on the left), each node in a given layer is connected to each node in the next layer. In contrast, hierarchical networks (right) are organized into subnets that capture specific system attributes by modeling subsets of related variables.

paper-based engineering drawings. A small reduction in the inputting cost for each drawing would represent huge savings because of the thousands of drawings that exist for each plant.

Alternative architecture

University of Maryland researchers are evaluating the performance of neural networks with a hierarchical architecture (RP8010-22). This design, which takes advantage of known relationships in the system or process being modeled, may represent an improvement over the typical three-layer network.

Typical neural networks have an internal structure that appears, in most respects, to be unrelated to the system being modeled. For example, networks designed to model systems with 25 variables have 25 input nodes and the same general structure regardless of specific system characteristics. Because typical networks have no a priori orientation about the likely features of input variables or about the relationships between variables, they are difficult to train. Moreover, once these networks are trained, it is difficult to evaluate their behavior, reliability, and applicability because the characteristics of input variables cannot be isolated to specific units or interconnections.

Hierarchical networks consist of a number of subnetworks arranged into layers (Figure 2). These subnets are loosely coupled, and the resulting networks have fewer interconnections and thus less computational complexity. Each subnet is intended to capture specific aspects of a system by modeling a subset of related system variables. By grouping related variables on the basis of prior knowledge, this modular organization provides hints to the network about important patterns and relationships and thus may accelerate training. It may also facilitate the evaluation of network performance because analyses can focus on the contributions of individual subnets.

Researchers have compared the performance of simple three-layer and hierarchical networks for several systems, including an oil heater. For the heater, nets were designed to estimate future outlet temperature on the basis of a fuel's specific gravity, the past flow rate, the past and future set points for flow rate, and the past outlet temperature.

The hierarchical network produced more accurate temperature predictions. Analyses of output signals from its subnets indicate that past temperature is the most important variable during initial time steps, that specific gravity has the strongest influence on outlet temperature over longer time periods, and that future flow rate set points become increasingly important with time. The influence of individual variables on temperature predictions made by the traditional network could not be determined. In ongoing work, researchers are conducting a theoretical investigation of the properties of hierarchical neural networks and developing a mathematical framework for this design approach.

The results of EPRI exploratory research indicate that neural network technology could improve the cost, efficiency, and safety of a variety of utility industry operations. The current research goal is to establish fundamental theory and reliable procedures for neural net design and development. Also, efforts to identify promising utility applications will continue.

New Contracts

Customer Systems

Project	Funding / Duration	Contractor / EPRI Project Manager
Assessment of Environmental and Safety Impacts of Batteries for Electric Vehicles (RP2415-38)	$100,000 11 months	Geomet Technologies / *R. Swaroop*
Nonintrusive Appliance Load Monitor (RP2568-23)	$385,300 40 months	Columbia University / *L. Carmichael*
Office Equipment Technology Improvement (RP2890-20)	$128,500 6 months	American Council for an Energy-Efficient Economy / *M. Blatt*
Commercial Electric Cooking Appliance Development Needs (RP2890-21)	$81,200 1 month	Tecogen / *W. Krill*
Electric Motor Load Studies (RP3087-21)	$175,000 10 months	Resource Dynamics Corp. / *B. Banerjee*
High-Frequency Electronic Ballast for Next-Generation Energy-Efficient Lighting System (RP3088-6)	$56,200 7 months	Tennessee Center for Research & Development / *B. Banerjee*
Power Electronics Devices and Components (RP3088-7)	$101,900 7 months	Tennessee Center for Research & Development / *B. Banerjee*
DSM Evaluation: Northern States Power and Madison Gas & Electric (RP3269-6)	$111,300 35 months	RLW Analytics / *P. Hummel*
Development of Advanced PRISM (RP3269-9)	$285,000 24 months	Princeton University / *P. Hummel*
Modifying Ice Crystal Habits and Growth Rate With Multiple Solutes (RP3280-30)	$50,000 15 months	University of Missouri, Columbia / *R. Wendland*
Inductive Charging Feasibility Study and System Development (RP3304-5)	$502,500 12 months	Hughes Aircraft Co. / *G. Purcell*
Food Processing Industry Wastewater Recovery Using Membrane Technology (RP3324-4)	$594,800 21 months	University of California, Davis / *A. Amarnath*
Evaluation of Non-Ozone-Depleting Heating and Cooling Systems (RP3412-4)	$149,900 12 months	Arthur D. Little / *W. Krill*
Novel HFC Propanes, HFC Butanes, and HFC Ethers as Alternatives to CFCs (RP3412-5)	$201,300 28 months	Clemson University / *P. Joyner*
Testing of Environmentally Safe Refrigerants and Refrigerant Mixtures in Residential and Commercial Heating and Cooling (RP3412-6)	$356,100 26 months	University of Maryland / *W. Krill*
User's Guide for the Application of Quality Function Deployment to Demand-Side Management (RP4001-1)	$118,700 10 months	Putnam, Hayes & Bartlett / *T. Henneberger*
Customer Needs Research: Organizational and Managerial Decision Making (RP4001-4)	$51,300 7 months	Bramson-Gill Associates / *T. Henneberger*

Electrical Systems

Project	Funding / Duration	Contractor / EPRI Project Manager
UCA/DAIS Exchange (RP2949-10)	$208,300 10 months	Plexus Research / *R. Iveson*
Distribution Engineering Workstation Development, Phase 1 (RP3079-2)	$726,500 13 months	Power Computing Co. / *H. Ng*
Error Correction Methods for Harmonics Measurements in Power Systems (RP3098-4)	$73,200 21 months	Georgia Institute of Technology Research Corp. / *H. Mehta*
Incremental Power Transfer Capability Study (RP3140-5)	$65,000 23 months	University of Missouri, Columbia / *N. Balu*
Cold Load Pickup Characterization (RP3155-11)	$138,300 23 months	Electrotek Concepts / *H. Mehta*
Efficiency of Energy Storage and Recovery Using the Very Incomplete Meissner Effect (RP4000-47)	$102,800 14 months	University of Houston / *M. Rabinowitz*

Environment

Project	Funding / Duration	Contractor / EPRI Project Manager
Firing of Low-Sulfur Coal: Effects on Gaseous Emissions (RP1835-28)	$325,500 27 months	Fossil Energy Research Corp. / *A. Kokkinos*
Evaluation of Fourier Transform Infrared Techniques for Continuous Emission Monitoring (RP1961-11)	$160,200 20 months	Entropy Environmentalists / *R. Glover*
Biotransformation of PCBs in Contaminated Soils: Microbiological and Molecular Studies (RP2879-23)	$500,000 53 months	University of Tennessee / *R. Goldstein*
Demonstration of XCL Low-NO_x Burner (RP2916-24)	$1,699,400 16 months	Southern Company Services / *J. Stallings*
Effects of Clean Air Act Compliance Coals on NO_x Emissions and Boiler Operations: Pilot-Scale Evaluation (RP2916-25)	$811,800 18 months	Southern Company Services / *J. Stallings*
EMF Information Project (RP2964-18)	$264,800 30 months	Robert S. Banks Associates / *S. Lindenberg*
Bioremediation of Mercury-Contaminated Sites (RP3015-4)	$155,900 18 months	University of West Florida / *R. Goldstein*
Utilization of FGD Gypsum and Bottom Ash in Roadway and Building Construction (RP3176-11)	$79,100 23 months	Texas A&M Research Foundation / *D. Golden*
Uncertainty in Chemical Mechanisms for Air Quality Modeling (RP3189-6)	$240,300 23 months	University of Connecticut / *A. Hansen*
Solidification Processing of Metal-Matrix Fly Ash ("Ashalloy") Composites (RP3275-1)	$645,400 57 months	University of Wisconsin, Milwaukee / *D. Golden*
Mercury Accumulation Pathways and Processes (RP3297-2)	$2,454,100 36 months	Wisconsin Department of Natural Resources / *D. Porcella*
Controlled Exposure of Mature Northern Red Oak Trees and Seedlings to Ozone (RP3315-1)	$1,482,000 35 months	Tennessee Valley Authority / *J. Huckabee*
GLOCO: Unispheric Global Carbon Cycle Model (RP3316-2)	$198,200 8 months	Tetra Tech / *R. Goldstein*
Method for Integrated Assessment of Water Resource Systems and Power Operations (RP3369-1)	$2,200,200 45 months	Tennessee Valley Authority / *D. McIntosh*
Induced Arsenite Tolerance in Human Cells (RP3370-3)	$60,000 10 months	New York University Medical Center / *L. Goldstein*
Lung Retention and Bioavailability of Arsenic in Fly Ash (RP3370-7)	$134,700 18 months	Catholic University of Louvain / *J. Yager*

Exploratory & Applied Research

Project	Funding / Duration	Contractor / EPRI Project Manager
Process-Induced Internal Stresses in Laminated Polymer Composites (RP8007-22)	$152,500 25 months	University of Washington / *J. Stringer*
Novel Polymeric Composites for Power Transmission Structures (RP8007-23)	$50,300 22 months	Georgia Institute of Technology Research Corp. / *J. Stringer*
Modeling CO_2 Disposal in the Ocean (RP8011-10)	$123,600 12 months	Science Applications International Corp. / *D. Spencer*
Genetic Ecology: Pentachlorophenol and Polycyclic Aromatic Hydrocarbon Degradation (RP8011-18)	$575,000 42 months	Rutgers University / *R. Goldstein*
Forest Dieback in Relation to Climate Change (RP8011-19)	$100,000 24 months	Science and Policy Associates / *L. Pitelka*
Effects of Architectural Lighting (RP8012-12)	$50,600 10 months	Jefferson Medical College / *R. Black*
Multidynamics: Methodology Development and Testing (RP9002-3)	$129,300 8 months	Decision Focus / *R. Schainker*

Generation & Storage

Project	Funding/ Duration	Contractor/EPRI Project Manager
Test Program With Pittsburgh Coal in the High-Temperature Winkler Pilot Plant (RP2656-7)	$800,000 6 months	Rheinbraun AG / *M. Epstein*
Lloyd Shoals Dissolved-Oxygen Hydro Project (RP2694-15)	$111,700 13 months	Georgia Power Co. / *D. Morris*
Intelligent Dynamic Control Optimization Project (RP2710-25)	$396,500 27 months	Georgia Power Co. / *J. Weiss*
User Interface for the Gas Turbine Outage Criteria Database (RP2831-8)	$115,600 22 months	Enter Software / *R. Frischmuth*
Siting Potential for CAES Plants in Western Area Power Administration Region (RP3049-14)	$124,500 5 months	Harza Engineering Co. / *B. Mehta*
Compact Simulator Technology Development and Demonstration (RP3152-14)	$187,000 12 months	Science Applications International Corp. / *M. Divakaruni*
Combustion Turbine Control System Development and Demonstration: Technical Support (RP3152-15)	$167,200 12 months	Science Applications International Corp. / *G. Poe*
AFBC Air, Waterside, and Materials Balance-of-Plant Guidelines (RP3162-6)	$79,600 5 months	Fluidized Bed Technologies / *T. Boyd*
AFBC Bed Material and Fly Ash Balance-of-Plant Guidelines (RP3162-7)	$57,000 5 months	Joseph Technology Corp. / *T. Boyd*
Fluidized-Bed Combustion Environmental Performance (RP3197-15)	$110,100 9 months	Combustion Systems / *R. Brown*
EPRIGEM for Plant Problem Characterization Guidelines (RP3220-17)	$54,200 3 months	Encor-America / *W. Piulle*
International Affiliates Technology Assessment (RP3220-25)	$106,800 12 months	Encor-America / *O. Gray*
Asbestos Control and Replacement (RP3246-3)	$751,900 22 months	Fluor Daniel / *S. Gehl*
Electric Utility Insulation Resource Measurement Program (RP3258-6)	$53,100 11 months	Daystar / *J. Bigger*
Power Plant Performance Instrumentation System (RP3383-1)	$1,200,000 12 months	Potomac Electric Power Co. / *E. Petrill*
Compact Simulator for Repowered Station (Lauderdale) (RP3384-3)	$659,900 16 months	Trax Corp. / *R. Fray*
Development of Westinghouse Expanders for CAES/CASH Service (RP3397-1)	$150,600 10 months	Westinghouse Electric Corp. / *R. Pollak*
CAES Component Development Coordination and Supervision (RP3397-2)	$195,000 32 months	Energy Storage & Power Consultants / *R. Pollak*
Gas Turbine and Combined-Cycle Capacity Enhancement (RP3401-1)	$845,300 21 months	Fern Engineering / *H. Schreiber*
Planning Frameworks for Wind Resources (RP3404-1)	$74,700 5 months	Decision Focus / *E. Davis*
Natural Gas–Fueled Molten Carbonate Fuel Cell Power Plant: Development and Demonstration (RP3472-1)	$4,300,000 48 months	San Diego Gas & Electric Co. / *R. Goldstein*
Development, Analysis, and Testing of L-1 Blade Repair or Replacement Options (RP3482-1)	$424,900 18 months	Stress Technology / *T. McCloskey*

Integrated Energy Systems

Project	Funding/ Duration	Contractor/EPRI Project Manager
Distributed Technology Evaluation Project, Phase 1 (RP2997-5)	$150,600 8 months	Applied Decision Analysis / *J. Bloom*
Utility Fuel Inventory Model Support (RP3344-25)	$121,700 12 months	Applied Decision Analysis / *C. Clark*
DYNAMICS Enhancements (RP3440-1)	$230,000 9 months	Decision Focus / *H. Fortune*
Integrated Standardized Database Scoping, Phase 2 (RP3443-1)	$196,400 10 months	Abacus Programming Corp. / *L. Rubin*
EPRICAD: CAD Link Software Development (RP3702-1)	$99,600 5 months	Karta Technology / *A. Kader*

Nuclear Power

Project	Funding/ Duration	Contractor/EPRI Project Manager
Severe-Accident Activities Support (RP1933-9)	$103,700 12 months	Altos Engineering Applications / *A. Machiels*
Pump Troubleshooting, Phase 1 (RP2520-10)	$99,800 7 months	Energy Research & Consultants Corp. / *J. Lang*
Methodology for Developing Fragility Curves (RP2722-32)	$125,200 13 months	Jack R. Benjamin & Associates / *R. Kassawara*
Dissolution of Chromium Carbides and of Oxides of Alloying Elements in Type 304 Stainless Steel and Inconel 600 in High-Temperature Water (RP2812-12)	$60,000 12 months	Ohio State University / *J. Gilman*
Uninterruptible Power Supply System Maintenance Guide (RP2814-48)	$95,300 7 months	Ebasco Services / *W. Johnson*
Development of Turbine Disk Ultrasonic Inspection Data Acquisition and Analysis System (RP2857-4)	$169,900 12 months	Sierra Matrix / *S. Liu*
Rule Sets for Electrical Drawing (RP3045-3)	$290,000 23 months	Wisconsin Electric Power Co. / *R. Colley*
Full-System Decontamination Study at Carolina Power & Light's Brunswick Plant: Engineering Study (RP3313-5)	$99,900 6 months	Pacific Nuclear Services / *C. Wood*
B&W Advanced Control System Integration (RP3338-2)	$2,275,600 48 months	B&W Nuclear Service Co. / *S. Bhatt*
Plant Computing Architecture Plan Methodology (RP3405-1)	$112,000 7 months	Queue Systems / *J. Naser*
Maintenance Rule Support (RP3409-1)	$97,900 12 months	Erin Engineering & Research / *D. Worledge*
Reactor Protection System Upgrade Using Safety-Grade Programmable Logic Controllers (RP3410-1)	$178,100 11 months	Spectrum Technologies USA / *S. Bhatt*
Performance Prediction Methodology for Motor-Operated Butterfly Valves (RP3433-22)	$379,500 25 months	Kalsi Engineering / *K. Wolfe*
Effect of Surface Film Electric Resistance on the Eddy-Current Detectability of Surface Cracks in Alloy 600 (RP3500-10)	$76,400 7 months	Valtion Teknillinen Tutkimuskeskus / *P. Paine*
License Renewal and Integrated Plant Assessment (RP3675-1)	$800,000 9 months	Multiple Dynamics Corp. / *J. Byron*
Evaluation of the Technical Bases for Averaging Nuclide Concentrations Over the Package Waste Volume (RP3800-13)	$65,900 7 months	Vance & Associates / *R. Williams*
Cooperative Research and Development Agreement for Instrumentation and Control R&D (RP4500-1)	$400,000 30 months	Martin Marietta Energy Systems / *J. Naser*
Measurement of Fracture Toughness Resistance Curves for Highly Irradiated Stainless Steel (RPC102-11)	$75,000 13 months	VTT (Technical Research Centre of Finland) / *J. Gilman*
BWR Pressure Vessel Nozzle Inspection Modeling (RPC105-9)	$120,000 8 months	Weidlinger Associates / *M. Avioli*
Utility Benefit Assessment of Steam Generator Products (RPS405-18)	$140,300 7 months	Decision Focus / *L. Williams*
Evaluation of Stress Corrosion Cracking Inhibitors for Steam Generators (RPS407-51)	$155,400 12 months	Babcock & Wilcox Co. / *P. Paine*
Survey of Steam Generator Shell Cracking (RPS407-52)	$136,500 9 months	Dominion Engineering / *A. McIlree*
Large-Eddy Simulations of Turbulent Flow in Steam Generators (RPS410-16)	$101,900 11 months	Texas A&M University / *D. Steininger*
Geometry Database for Steam Generator Fatigue and Wear (RPS415-1)	$124,600 8 months	CFD Research Corp. / *G. Srikantiah*
GUST Code Verification and Documentation (RPS415-3)	$243,300 19 months	CFD Research Corp. / *G. Srikantiah*
Correlation Between Grain Boundary Composition and Stress Corrosion Cracking Susceptibility (RPX102-5)	$51,500 9 months	Modeling & Computing Services / *L. Nelson*
UO_2 and (U,Gd) O_2 Irradiated to High Burnup: Measurements of Fuel Properties as a Function of Burnup (RPX102-22)	$551,800 20 months	Belgonucleaire / *S. Yagnik*

New Technical Reports

Requests for copies of reports should be directed to the EPRI Distribution Center, 207 Coggins Drive, P.O. Box 23205, Pleasant Hill, California 94523; (510) 934-4212. There is no charge for reports requested by EPRI member utilities and affiliates. Reports will be provided to nonmember U.S. utilities only upon purchase of a license, the price of which will be equal to the price of EPRI membership. Others pay the listed price or, in some cases (when noted), must enter into a licensing agreement.

CUSTOMER SYSTEMS

Manufactured Housing: Energy Use Assessment
TR-100429 Final Report (RP2597-27); $200
Contractor: Barrett Consulting Associates, Inc.
EPRI Project Manager: A. Lannus

Improving Management of Low-Temperature Drying of Corn
TR-100445 Final Report (RP2782-4); $200
Contractors: National Food and Energy Council, Purdue University
EPRI Project Managers: A. Amarnath, O. Zimmerman

Perceptions of Compact Fluorescent Lamps in the Residential Market
TR-100734 Final Report (RP2597-31, RP3249); $200
Contractor: MACRO Consulting, Inc.
EPRI Project Managers: M. Evans, J. Kesselring

Rural Water/Wastewater Study, Vol. 1: Background, Terminology, and Recommendations
TR-100820 Final Report (RP2662-20), Vol. 1, $200
Contractor: Kennedy/Jenks Consultants
EPRI Project Manager: M. Jones

Cool Storage Ethylene Glycol Design Guide
TR-100945 Final Report (RP3280-3); $200
Contractor: Gatley & Associates, Inc.
EPRI Project Manager: R. Wendland

Engineering Methods for Estimating the Impacts of Demand-Side Management Programs, Vol. 1: Fundamentals of Engineering Simulations for Residential and Commercial End Uses
TR-100984 Final Report (RP3269-3); $200
Contractor: Architectural Energy Corp.
EPRI Project Manager: P. Hanser

Electrotechnology Reference Guide, Revision 2
TR-101021 (Rev. 2) Final Report (RP2613-10); $200
Contractor: Resource Dynamics Corp.
EPRI Project Manager: M. Jones

Advanced Lighting Technologies Application Guidelines: 1990
TR-101022 Final Report (RP2285-26); $200
Contractor: Eley Associates
EPRI Project Manager: K. Johnson

Ice Storage Rooftop Retrofit Performance
TR-101038 Final Report (RP3280-1); $200
Contractor: Denkmann Thermal Storage, Inc.
EPRI Project Manager: R. Wendland

Activity-Based Costing for Electric Utilities
TR-101065 Final Report (RP2982-14); $200
Contractor: Venture Associates
EPRI Project Manager: P. Hanser

Assessment of Gas and Electric Cooling Equipment
TR-101142 Final Report (RP3138-2); $200
Contractor: Energy International, Inc.
EPRI Project Manager: M. Blatt

ESPRE 2.1 Engineering Model: Simplified Energy Analysis Methods for Residential Buildings
TR-101189 Final Report (RP2034-33), $200
Contractor: Arthur D. Little, Inc.
EPRI Project Manager: J. Kesselring

ELECTRICAL SYSTEMS

Survey of Residential Magnetic Field Sources: Interim Report
TR-100194 Interim Report (RP2942-6); $200
Contractors: General Electric Co.; Enertech Consultants, Inc.; Electric Research and Management
EPRI Project Managers: G. Rauch, J. Dunlap

Development of Production Software for the Economic Evaluation of Distribution Automation Functions, Vols. 1–3
TR-100398 Computer Code Manual (RP2021-2); Vols. 1–3, license required
Contractor: Power Computing Co.
EPRI Project Manager: T. Kendrew

Power System Steady-State Stability Monitor Prototype, Vols. 1 and 2
TR-100799 Final Report (RP2473-43), Vols. 1 and 2, $200 each volume
Contractor: SYDETECH System Development Technologies, Inc.
EPRI Project Manager: R. Adapa

Microscopic Probes of High-Temperature Superconductivity
TR-100862 Final Report (RP7911-15); $200
Contractor: Virginia Commonwealth University
EPRI Project Manager: M. Rabinowitz

Seasonal Variations of Grounding Parameters by Field Tests
TR-100863 Interim Report (RP1494-8); $200
Contractor: SEI/Georgia Power Research Center
EPRI Project Manager: G. Addis

Feasibility Study to Manufacture Dry-Cure Cables by Internal Pressurization Process
TR-100905 Final Report (RP1593-1); $750
Contractor: Cable Technology Laboratories, Inc.
EPRI Project Manager: B. Bernstein

ENVIRONMENT

Economic Evaluation of Particulate Control Technologies, Vol. 1: New Units
TR-100748 Final Report (RP3083-4); $750
Contractor: Sargent & Lundy
EPRI Project Manager: R. Chang

CHROMAT™ Version 1.1 (Soil Chromium Attenuation Evaluation Model): User's Manual and Technical Reference
TR-100765 Interim Report (RP2485-3); $200
Contractor: Battelle, Pacific Northwest Laboratories
EPRI Project Managers: M. Elrashidi, I. Murarka

Comanagement of Coal Combustion By-products and Low-Volume Wastes: A Midwestern Site
TR-100955 Interim Report (RP2485-9); $200
Contractors: Radian Corp., GeoTrans, Inc., Battelle, Pacific Northwest Laboratories
EPRI Project Managers: I. Murarka, J. Goodrich-Mahoney

Estimating Release of Polycyclic Aromatic Hydrocarbons From Coal Tar at Manufactured-Gas Plant Sites
TR-101060 Interim Report (RP2879-7); $200
Contractor: University of Texas, Austin
EPRI Project Manager: M. Elrashidi

Strategies for Field Calibration and Validation of Groundwater Models
TR-101063 Interim Report (RP2485-9); $200
Contractor: Battelle, Pacific Northwest Laboratories
EPRI Project Manager: I. Murarka

Application of MYGRT™ V2.0 to a Manufactured-Gas Plant Site
TR-101064 Interim Report (RP2879-6); $200
Contractor: Remediation Technologies, Inc.
EPRI Project Manager: I. Murarka

Boiler Chemical Cleaning Waste Management Manual
TR-101095 Final Report (RP2215-1); $200
Contractor: Radian Corp.
EPRI Project Managers: T. Lott, W. Micheletti, M. Miller

Design Guidelines for Targeted Chlorination With Fixed Nozzles
TR-101096 Final Report (RP2300-2); $200
Contractor: Stone & Webster Engineering Corp.
EPRI Project Manager: W. Chow

Fish Entrainment and Turbine Mortality Review and Guidelines
TR-101231 Final Report (RP2694-1); $200
Contractor: Stone & Webster Environmental Services
EPRI Project Managers: J. Mattice, C. Sullivan

EXPLORATORY & APPLIED RESEARCH

Bifurcation and Chaos in Power Systems: A Survey
TR-100834 Final Report (RP8010-10); $200
Contractor: University of California, Berkeley
EPRI Project Manager: M. Lauby

GENERATION & STORAGE

Uplift Pressures, Shear Strengths, and Tensile Strengths for Stability Analysis of Concrete Gravity Dams, Vol. 1

TR-100345 Final Report (RP2917-5); Vol. 1, $200
Contractor: Stone & Webster Engineering Corp.
EPRI Project Manager: D. Morris

Grimethorpe High-Temperature/High-Pressure Gas Filter Experimental Program, Vols. 1–4

TR-100499 Final Report (RP1336-8), Vols. 1–4, $200 each volume
Contractor: British Coal Corp.
EPRI Project Manager: J. Stringer

Atmospheric Fluidized-Bed Combustion Fabric Filter Monitoring

TR100562 Final Report (RP2303-21); $200
Contractor: Southern Research Institute
EPRI Project Manager: T. Boyd

Waste-to-Energy Screening Guide, Vols. 1 and 2

TR-100670 Final Report (RP2190-5), Vols. 1 and 2, $1800 for set
Contractor: Bechtel Group, Inc.
EPRI Project Manager: E. Hughes

Third International Conference on Improved Coal-Fired Power Plants

TR-100848 Proceedings; $200
EPRI Project Managers: S. Pace, G. Poe

Creep-FatiguePro: On-line Creep-Fatigue Damage and Crack Growth Monitoring System

TR-100907 Final Report (RP1893-11); $200
Contractor: Structural Integrity Associates, Inc.
EPRI Project Managers: J. Scheibel, R. Pflasterer

Rotor Dynamic Modeling and Testing of Boiler Feedpumps

TR-100980 Final Report (RP1884-10); $200
Contractor: Sulzer Brothers, Ltd.
EPRI Project Managers: S. Pace, T. McCloskey

Gasification of Pittsburgh No. 8 Coal in Rheinbraun's Atmospheric High-Temperature Winkler Process Development Unit

TR-100983 Final Report (RP2656-5), $200
Contractor: Rheinbraun
EPRI Project Manager: M. Epstein

Hydraulic and Mechanical Interactions of Feedpump Systems

TR-100990 Final Report (RP1884-10), $200
Contractor: Sulzer Brothers, Ltd.
EPRI Project Managers: S. Pace, T. McCloskey

Proceedings: Conference on Asbestos Control and Replacement for Electric Utilities

TR-101093 Proceedings (RP3246); $200
EPRI Project Manager: M. Blanco

Electric Motors Using Superconducting Materials Applied to Power Generating Station Equipment

TR-101127 Interim Report (RP3149-1, RP7911-2); $200
Contractor: Reliance Electric Co.
EPRI Project Manager: J. Stein

INTEGRATED ENERGY SYSTEMS

Availability Assessment of Energy Research Corporation's 2-MW Carbonate Fuel Cell Demonstration Power Plant

TR-101107 Final Report (RP3199-5), $200
Contractor: ARINC Research Corp.
EPRI Project Manager: D. Rastler

Natural Gas for Electric Generation: The Challenge of Gas and Electric Industry Coordination

TR-101239 Final Report (RP3201-1, -2, -4, -5); $200
Contractors: Charles River Associates, Inc., Energy Ventures Analysis, Inc.; Jensen Associates, Inc.
EPRI Project Managers: H. Mueller, J. Platt

NUCLEAR POWER

MULTEQ (Equilibrium of an Electrolytic Solution With Vapor-Liquid Partitioning), Vol. 3: Theory Manual

NP-5561-CCML Computer Code Manual (RPS407-30), Vol. 3, license required
Contractor: Maxwell Laboratories, Inc.
EPRI Project Managers: P. Paine, P. Millett

Determination of Thermodynamic Data for Modeling Corrosion, Vol. 5: $NiCl_2$, $CuCl_2$, HNO_3, $Ni(NO_3)_2$, $NaNO_3$ Systems

NP-5708 Final Report (RPS407-1), Vol. 5, $200
Contractor: Brigham Young University
EPRI Project Managers: P. Paine, P. Millett

Water Hammer Prevention, Mitigation, and Accommodation, Vol. 2: Root Cause Analysis for Plant Water Hammer Experience

NP-6766 Final Report (RP2856-3); Vol. 2, license required
Contractors: Stone & Webster Engineering Corp.; Bechtel Group, Inc.
EPRI Project Manager: M. Merilo

Water Hammer Prevention, Mitigation, and Accommodation, Vol. 4, Part 1: Review of Analytic Models and Computer Codes—Sample Problems and Comparisons

NP-6766 Final Report (RP2856-3), Vol. 4, Part 1, license required
Contractors: Stone & Webster Engineering Corp., Bechtel Group, Inc.
EPRI Project Manager: M. Merilo

Water Hammer Prevention, Mitigation, and Accommodation, Vol. 4, Part 2: Review of Analytic Models and Computer Codes—Theoretical Bases

NP-6766 Final Report (RP2856-3), Vol. 4, Part 2, license required
Contractors: Stone & Webster Engineering Corp.; Bechtel Group, Inc.
EPRI Project Manager: M. Merilo

Water Hammer Prevention, Mitigation, and Accommodation, Vol. 5, Part 1: Assessment Guidelines

NP-6766 Final Report (RP2856-3); Vol. 5, Part 1, license required
Contractor: Stone & Webster Engineering Corp.
EPRI Project Manager: M. Merilo

Water Hammer Prevention, Mitigation, and Accommodation, Vol. 5, Part 2: Prevention Guidelines

NP-6766 Final Report (RP2856-3); Vol. 5, Part 2, license required
Contractor: Stone & Webster Engineering Corp.
EPRI Project Manager: M. Merilo

Water Hammer Prevention, Mitigation, and Accommodation, Vol. 5, Part 3: Diagnostic Guidelines

NP-6766 Final Report (RP2856-3), Vol. 5, Part 3, license required
Contractors: Stone & Webster Engineering Corp.; Failure Prevention, Inc.
EPRI Project Manager: M. Merilo

Water Hammer Prevention, Mitigation, and Accommodation, Vol. 6: Review of Plant Systems and Procedures

NP-6766 Final Report (RP2856-3), Vol. 6, license required
Contractors: Stone & Webster Engineering Corp.; Bechtel Group, Inc.
EPRI Project Manager: M. Merilo

Outside Diameter Stress Corrosion Cracking of Steam Generator Tubing at Tube Support Plates: A Database for Alternate Repair Limits—Vol. 1, 7/8-Inch Tubing

NP-7480-L Final Report (RPS404-29); Vol. 1, license required
Contractor: Westinghouse Electric Corp.
EPRI Project Manager: L. Williams

Preconditioning of PWR Steam Generators to Reduce Radiation Buildup

TR-100217 Final Report (RP2758-5); $200
Contractor: Commissariat à l'Energie Atomique
EPRI Project Manager: C. Wood

Steam Generator Channel Head Dose Rates at Babcock & Wilcox Reactors

TR-100348 Final Report (RP2494-4), $200
Contractor: B&W Nuclear Services Co.
EPRI Project Manager: H. Ocken

Proceedings: 1991 EPRI Radwaste Workshop

TR-100555 Proceedings (RP2414-28), $200
Contractor: Ascent Services
EPRI Project Manager: C. Hornibrook

Generic Scaling Factors for Dry Active Wastes

TR-100740 Final Report (RP2414-41); $200
Contractor: Vance & Associates
EPRI Project Manager: C. Hornibrook

New Technology in Condensate Polishing

TR-100757 Final Report (RP1571-9); $200
Contractor: Graver Co.
EPRI Project Manager: T. Passell

Demineralizer Operation With Morpholine and Boric Acid

TR-100790 Topical Report (RPS409-3); $200
Contractor: NWT Corp.
EPRI Project Manager: T. Passell

Mercury Modeling for PWSCC Length Sizing

TR-101104 Interim Report (RPS404-28); $2000
Contractor: Westinghouse Science & Technology Center
EPRI Project Manager: M. Behravesh

New Computer Software

The Electric Power Software Center (EPSC) provides a single distribution center for computer programs developed by EPRI. The programs are distributed under license to users. EPRI member utilities, in paying their membership fees, prepay all royalties. Nonmember organizations licensing EPRI computer programs are required to pay royalties. For more information about EPSC and licensing arrangements, EPRI member utilities should contact the Electric Power Software Center, Power Computing Co., 1930 Hi Line Drive, Dallas, Texas 75207; (214) 655-8883. Other organizations should contact EPRI's Manager of Licensing, P.O. Box 10412, Palo Alto, California 94303; (415) 855-2866.

ARA: Acid Rain Advisor
Version 1.0 (PC-OS/2)
Developer: Black & Veatch
EPRI Project Manager: Dave O'Connor

BTA™: Bearing Troubleshooting Advisor
Version 1.0 (CD-ROM)
Developer: Automation Technology
EPRI Project Manager: Tom McCloskey

CHROMAT™: Soil Chromium Attenuation Evaluation Model
Version 1.1 (PC-DOS)
Developer: Battelle PLC
EPRI Project Manager: Moustafa Elrashidi

CREAM: Composite Reliability Assessment by Monte Carlo
Version 1.2 (DEC-VMS; IBM-MVS; PC-DOS)
Developer: Power Systems Research, Inc.
EPRI Project Manager: Neal Balu

DIRECT: Direct Stability Analysis Program
Version 3.0 (IBM-MVS)
Developer: Ontario Hydro
EPRI Project Manager: Gerry Cauley

DYNRED: Dynamic Reduction Program
Version 1.0 (DEC-VMS; IBM-MVS; Prime-PRIMOS)
Developer: Ontario Hydro
EPRI Project Manager: Neal Balu

RETRAN-03: A Program for Transient Thermal-Hydraulic Analysis
Version MOD000 (PC386/486-DOS)
Developer: Computer Science & Analysis
EPRI Project Manager: Lance Agee

TAG Supply™: Technical Assessment Guide for Supply-Side Technologies
Version 2.0 (PC-DOS)
Developer: EPRI
EPRI Project Manager: G. Ramachandran

VTester™: A Tool for Managing Reactor Vessel Embrittlement Decisions
Version 2.0 (PC-DOS)
Developer: Decision Focus, Inc.
EPRI Project Manager: Tim Griesbach

EPRI Events

MARCH

1–3
International Symposium on Improved Technology for Fossil Power Plants: New and Retrofit Applications
Washington, D.C.
Contact: Lori Adams, (415) 855-8763

2–4
NDE for Fossil Plants
Eddystone, Pennsylvania
Contact: John Niemkiewicz, (215) 595-8871

24–26
6th National DSM Conference
Miami, Florida
Contact: Pam Turner, (415) 855-2010

29–April 2
ETADS Seminar
Haslet, Texas
Contact: Paul Lyons, (817) 439-5900

30–April 1
Biomass and Waste Fuels
Washington, D.C.
Contact: Susan Bisetti, (415) 855-7919

APRIL

1–2
Dynamics of Interconnected Power Systems
St. Petersburg, Florida
Contact: Gerry Cauley, (415) 855-2832

5–8
10th Particulate Control Symposium
Washington, D.C.
Contact: Lori Adams, (415) 855-8763

13–15
Continuous Emissions Monitoring
Baltimore, Maryland
Contact: Linda Nelson, (415) 855-2127

20–22
Achieving Accurate Coal Weighing and Sampling Systems
St. Louis, Missouri
Contact: Barbara Fyock, (412) 479-6015

27–30
Transformer Performance Monitoring and Diagnostics
Eddystone, Pennsylvania
Contact: John Niemkiewicz, (215) 595-8871

MAY

3–5
Nuclear Plant Support Engineering Products and Issues
Atlanta, Georgia
Contact: Sheryl McBane, (704) 547-6086

5–7
Plant Communications and Computing Architectures, Control Rooms, and Workstations
Tampa, Florida
Contact: Linda Nelson, (415) 855-2127

10–11
Nuclear Plant Performance Improvement
Scottsdale, Arizona
Contact: Susan Otto, (704) 547-6072

19–21
Rotating Machinery Vibration
San Diego, California
Contact: Susan Bisetti, (415) 855-7919

23–27
EPRI/EPA Joint Symposium on Stationary Combustion NO_x Control
Miami, Florida
Contact: Pam Turner, (415) 855-2010

JUNE

7–9
ISA POWID–EPRI Controls and Instrumentation Conference (Nuclear and Fossil)
Phoenix, Arizona
Contact: Lori Adams, (415) 855-8763

7–11
High-Voltage Transmission Line Electric Design Seminar
Lenox, Massachusetts
Contact: Joe Slocik, (413) 494-3320

8–10
Cooling Tower Performance Prediction and Improvement
Eddystone, Pennsylvania
Contact: John Niemkiewicz, (215) 595-8871

14–16
Seminar on Advanced Concepts in Line Structure Evaluation Techniques
Haslet, Texas
Contact: Paul Lyons, (817) 439-5900

14–16
Technology Transfer
San Francisco, California
Contact: Susan Bisetti, (415) 855-7919

15–16
Low-Level Mixed Waste Conference
Boston, Massachusetts
Contact: Linda Nelson, (415) 855-2127

15–18
Boiler Tube Failures: Correction, Prevention, and Control
Eddystone, Pennsylvania
Contact: John Niemkiewicz, (215) 595-8871

29–July 1
Heat Exchanger Performance Prediction
Eddystone, Pennsylvania
Contact: John Niemkiewicz, (215) 595-8871

Contributors


Davis


DeMeo


Dostalek


Goodman


Richels

A Growth Market in Wind Power (page 4) was written by Leslie Lamarre, *Journal* senior feature writer, with information provided by two members of EPRI's Generation & Storage Division.

Earl Davis, manager of wind power integration, joined the Institute early this year after 10 years with U.S. Windpower, where he was most recently director of international business development. Previously he worked for Windfarms, Ltd., and for Pacific Gas and Electric. Davis has a BS in meteorology and climatology from the University of Washington.

Edgar DeMeo, manager of the Solar Power Program, joined EPRI in 1976. Before that, he was a research associate professor of engineering at Brown University. As a lieutenant in the U.S. Naval Reserve from 1967 to 1969, he taught in the Science Department at the U.S. Naval Academy. He received a bachelor's degree in electrical engineering from Rensselaer Polytechnic Institute and MS and PhD degrees in engineering from Brown. ■

High Hopes for High-Power Solar (page 16) was written by Taylor Moore, *Journal* senior feature writer, with assistance from **Edgar DeMeo** and two other members of the Solar Power Program.

Frank Dostalek, a project manager, came to EPRI in 1986 with a background in industrial engineering. Dostalek worked for 15 years in several semiconductor R&D and materials manufacturing positions and has been involved with solar technology since 1977. He graduated from the University of Omaha in 1967.

Frank Goodman, also a project manager, joined EPRI in 1979 from the Los Angeles Department of Water & Power. Goodman, who earned BS, MS, and PhD degrees in electrical engineering from the University of California at Santa Barbara, has taught electrical engineering at UCSB, the University of Southern California, and Loyola Marymount University. ■

The Cost of Greenhouse Insurance (page 26) was written by science writer John Douglas with assistance from **Richard Richels,** director of EPRI's Energy Analysis & Planning Department. Richels has been with the Institute since 1976, having managed the Environmental Risk Analysis and Integrated Utility Planning programs before taking his present position. He was formerly a consultant to the Rand Corporation and the National Science Foundation. A physics graduate of the College of William and Mary, Richels earned MS and PhD degrees from Harvard University's Division of Applied Sciences. ■

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