# THE FULL PORTFOLIO

An aggressive strategy to cut carbon dioxide emissions and meet electricity demand between now and 2030 requires equally aggressive research, development, and demonstration for several advanced technologies.

BY REVIS JAMES

To lessen the potential threats of climate change, many scientists and policymakers envision large-scale reductions in carbon dioxide ($CO_2$) emissions—the goal is to ultimately stabilize global concentrations of $CO_2$, the most common greenhouse gas (GHG). Achieving such reductions, however, presents major technical, economic, regulatory and policy challenges. Reconciling those challenges with the continued growth in energy demand over the next 25 years calls for a diverse, economy-wide approach.

EPRI's most recent research focuses on a portfolio of seven advanced technologies—end-use energy efficiency, renewable energy, advanced light water nuclear reactors, advanced coal power plants, $CO_2$ capture and storage, plug-in hybrid electric vehicles (PHEVs), and distributed energy resources. EPRI found that, together, these technologies could reduce the estimated cost of $CO_2$ emissions reductions to the U.S. economy by $1 trillion. But the technology development and deployment effort must be aggressive, and the emphasis is on "together": No single technology will provide a majority of $CO_2$ emissions reductions.

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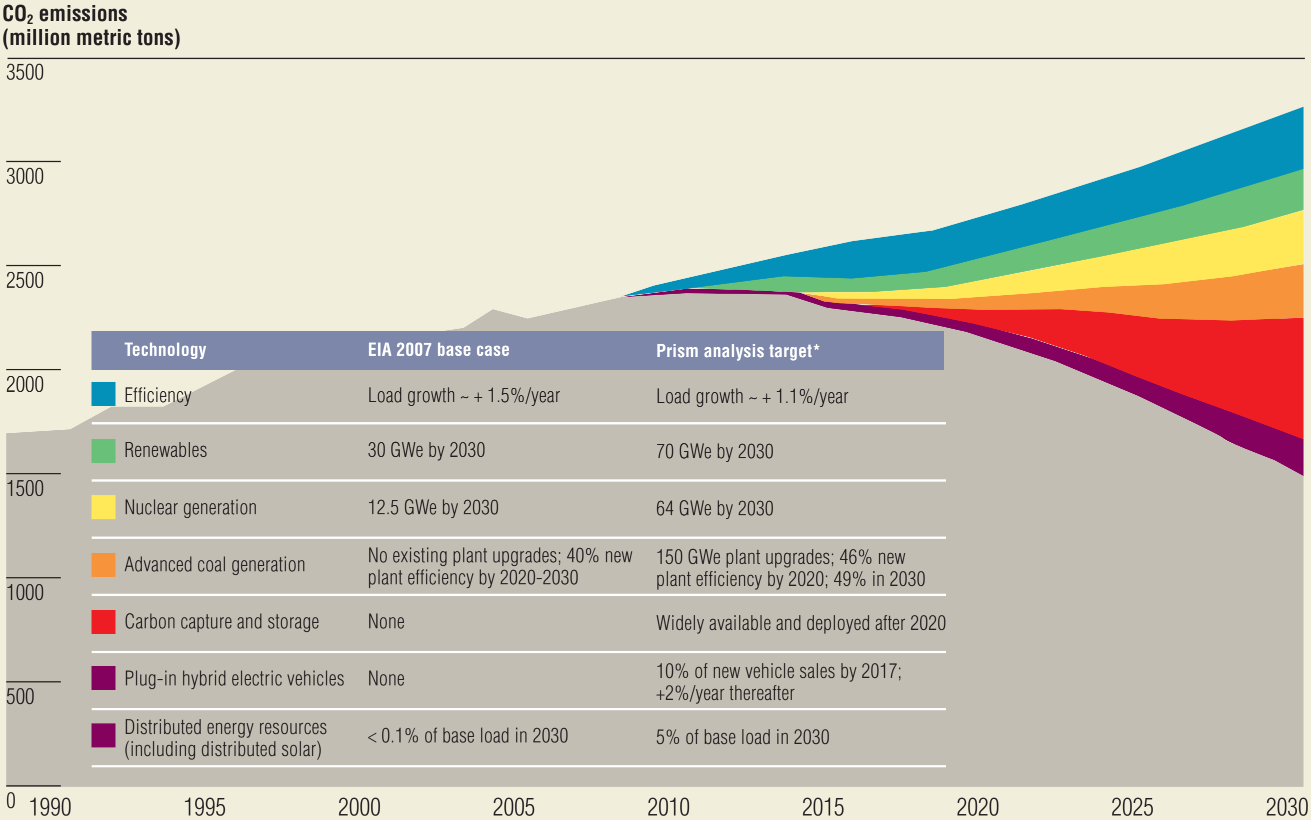
**TABLE 1**

**U.S. ELECTRIC SECTOR**




| | Technology | EIA 2007 base case | Prism analysis target* |
|---|---|---|---|
| ■ (blue) | Efficiency | Load growth ~ + 1.5%/year | Load growth ~ + 1.1%/year |
| ■ (green) | Renewables | 30 GWe by 2030 | 70 GWe by 2030 |
| ■ (yellow) | Nuclear generation | 12.5 GWe by 2030 | 64 GWe by 2030 |
| ■ (orange) | Advanced coal generation | No existing plant upgrades; 40% new plant efficiency by 2020-2030 | 150 GWe plant upgrades; 46% new plant efficiency by 2020; 49% in 2030 |
| ■ (red) | Carbon capture and storage | None | Widely available and deployed after 2020 |
| ■ (purple) | Plug-in hybrid electric vehicles | None | 10% of new vehicle sales by 2017; +2%/year thereafter |
| ■ (purple) | Distributed energy resources (including distributed solar) | < 0.1% of base load in 2030 | 5% of base load in 2030 |

* Prism analysis targets do not reflect economic or potential regulatory and siting constraints.

The EPRI analyses involve three related studies, the third of which—a technology development pathways analysis—sketched out four areas on which the electricity sector needed to focus. More important, it identified the research, development, and demonstration (RD&D) activities the sector would have to undertake to hit the required technology performance and deployment levels. The analysis also made preliminary estimates of what the RD&D capital investment would be.

Given the 20- to 30-year lead-time needed to fully research, develop, and commercially deploy technologies, the challenges are indeed great. And the effort will involve a substantial and prolonged public-private RD&D effort.

*Revis James is director of the Electric Power Research Institute's Energy Technology Assessment Center. This article is based on an August 2007 EPRI discussion paper, "The Power to Reduce $CO_2$ Emissions: The Full Portfolio." For more information, visit www.epri.com.*

## Measuring Potential First

The first study was the "Prism" analysis (so-called because of its graphical representation, shown in Figure 1) which determined the electricity sector's potential for reducing emissions from a purely technical perspective, based on deploying the advanced technology portfolio.

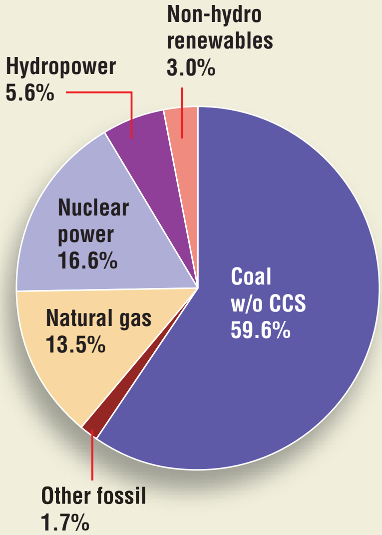
The selection of "aggressive but feasible" performance and deployment targets for these seven technologies was based on technological capabilities that still have RD&D challenges but also a specific sequence of RD&D activities leading to these targets between today and 2030.

To estimate $CO_2$ emissions reductions, the Prism analysis calculated a national electricity generation mix based on the targets and then calculated the change in emissions relative to the Energy Information Agency's (EIA's) 2007 Annual Energy Outlook base case. The result? Given successful, aggressive RD&D of the full portfolio, it is technically feasible to reduce annual emission levels by roughly 45 percent relative to EIA's 2030 projections. But there is no single "silver bullet" technology.

Also, aggressive implementation of advanced technologies provides a significant shift in the generation mix compared to EIA projections. (See Figure 2.) Coal remains a critical part of U.S. electricity supply, albeit with $CO_2$ capture; nuclear energy and renewables expand their share; and natural gas-fired generation declines. Also note that the estimated total electricity consumption in 2030 remains approximately the same in both the EIA and Prism analyses. This is due to improvements in energy efficiency and increas-

**FIGURE 2**

**EIA BASE CASE***
(5406 TWh)




*Base case from EIA "Annual Energy Outlook 2007"

**ADVANCED TECHNOLOGY TARGETS**
(5401 TWh)

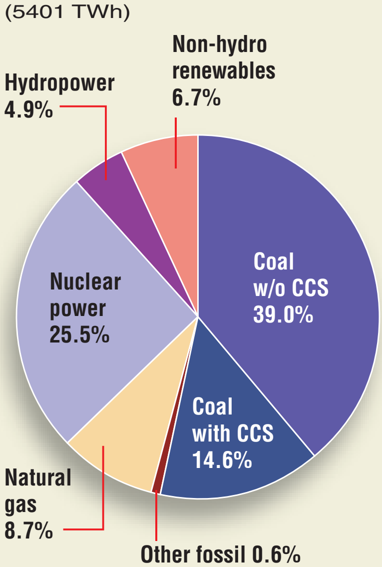
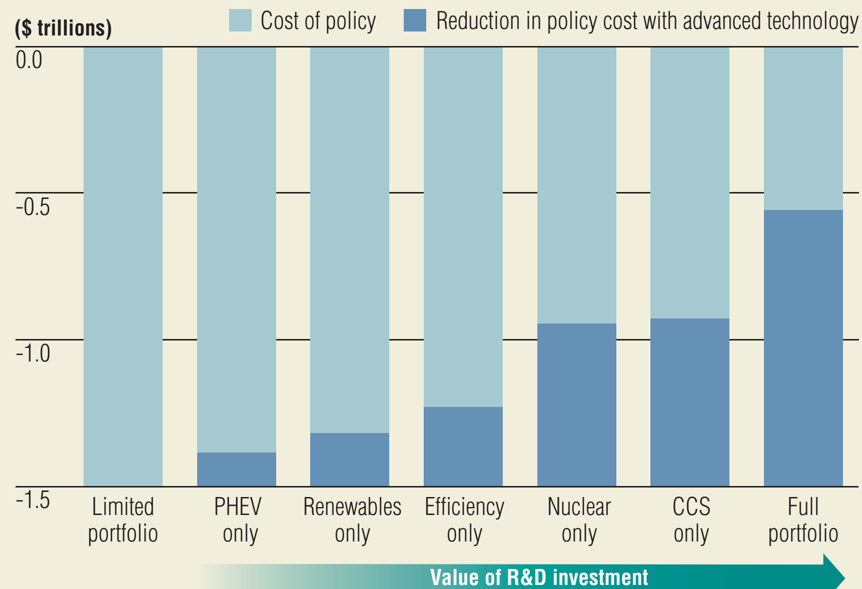



**FIGURE 3**

**CHANGE IN GROSS DOMESTIC PRODUCT DISCOUNTED THROUGH 2050***




* In year 2000 dollars

ing distributed generation, offset by increased electricity demand associated with PHEVs.

### Finding Value through MERGE Analysis

The goal of the MERGE (model for estimating the regional and global effects of greenhouse gas reductions) analysis was to study—in terms of cost, availability, and performance—the least-cost technology mix that could reach specific $CO_2$ emissions targets. MERGE studies long time horizons to capture economic effects of potential climate change and encompasses all major GHGs and all sectors of the economy. It is a global model, with detailed submodels of the United States and representative submodels of other regions of the world. MERGE is one of the principal modeling systems used for integrated assessment of international and U.S. climate policies.

The full portfolio represents substantially more improvement in performance and costs for a range of technologies, thus allowing their widespread deployment. In the full portfolio, for example, the MERGE analysis assumed that by 2020 $CO_2$ capture and storage would be commercially available, nuclear power production could expand significantly, and PHEVs would be widely available. None of these options are available in the limited portfolio.

The MERGE analysis assumed a carbon constraint which requires stabilization of annual $CO_2$ emissions at 2010 levels through 2020 and then a 3-percent annual decline in emissions. MERGE determined the constraint's economic impact in terms of the change in gross domestic product, finding a $1.5 trillion impact associated with the limited portfolio. For the full portfolio, the impact is $500 billion. (See Figure 3.)

The availability of technology has a large impact on wholesale electricity prices and the U.S. generation mix. For the limited portfolio, for example, emissions reductions require large reductions in electricity consumption, and wholesale electricity prices are extremely high to incent such reductions. In contrast, the availability of carbon capture and storage and nuclear generation in the full portfolio provide large-scale supply-side emissions reductions, protecting the electricity market and limiting the rise in wholesale electricity prices. In the end, availability of advanced generation technologies results in substantially lower wholesale electricity costs: For the full portfolio, costs increase 45 percent between 2000 and 2050, compared to a 265-percent increase for the limited portfolio.

The extent of advanced technology development and deployment also influences natural gas usage and pric-

Light water reactor technology is used in more than 80 percent of the world's current reactors, including the Tomari plant in Japan (inset). Third-generation nuclear power plants, such as the Olkiluoto 3 plant in Finland (above), will produce significantly reduced volumes of spent fuel and offer improved safety and plant control systems by using digital control technology.

ing. In the limited portfolio scenario, achieving required emissions reductions requires a significant amount of fuel switching to natural gas for electricity generation, as well as large reductions in electricity demand. This drives up natural gas prices substantially. By 2050, natural gas consumption by electric companies in the limited portfolio scenario is more than five times higher than the full portfolio scenario.

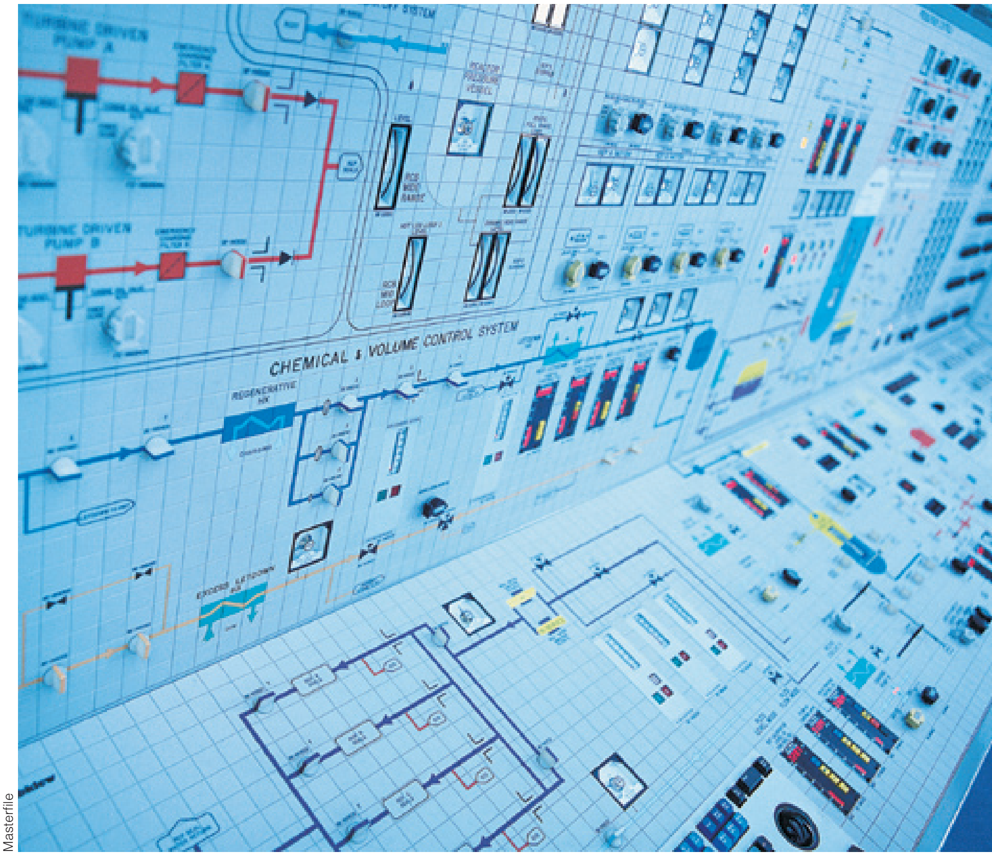
One key insight from the MERGE analysis is the opportunity for electricity to provide low-carbon energy throughout the economy. In particular, advanced technology allows the electricity price to remain relatively stable, which provides a "decarbonization" option for other sectors of the economy—transportation, in particular. This results in increased electrification in the economy.

**Technology Pathway 1: Nuclear Power**

*Deployment of advanced light water reactors, continued safe and economic operation of the existing nuclear fleet, and a viable strategy for managing spent fuel.*

Nuclear power's contribution to $CO_2$ emissions reductions hinges on the continued safe and economic performance of the existing fleet, which in the United States currently accounts for more than 20 percent of all gen-

Courtesy: Areva




Masterfile

Courtesy: Mitsubishi Heavy Industries, Ltd

eration and 70 percent of emissions-free generation. Additional reductions are possible through new nuclear plant development, since nuclear power is currently the only technologically mature nonemitting generation source that is proven and ready for deployment on a large scale. Nuclear energy's R&D needs, therefore, span both the current fleet and new plant construction.

The near-term technology needs for nuclear energy in the United States relate to light water reactor (LWR) technology, which is the technology used in more than 80 percent of the world's current reactors. Sustaining electricity production from these plants will require RD&D in the areas of facility life extension, digital control technology for both safety and plant control systems, and highly reliable, high burnup nuclear fuel capable of longer outage cycles, and significantly reduced volumes of spent fuel.

After more than two decades of investment in design development and prelicensing, advanced LWR designs are approaching "essentially complete design" status. Some ALWRs are in commercial operation or under construction in Japan, Korea, Taiwan, France, and Finland. In the United States, 15 utilities have stated their intent to apply for operating licenses based on ALWR designs. Additional RD&D will ensure that these new reactors maximize performance levels of safety, capacity factor, and reliability, comparable to levels in the existing fleet. For example, the industry must resolve generic regulatory issues—including criteria for digital instrumentation and control design technology, high-frequency seismic design, and quality assurance—to support the operation of new plants.

Courtesy: Battelle

**Overcoming technological challenges. High-temperature gas reactors, such as this one in China (inset), provide a technology option to reduce $CO_2$ emissions from large consumers of primary energy. An 8,000-foot well (above) has been completed at FirstEnergy's Burger plant near Shadyside, OH, in preparation for a geologic sequestration field test. In operation since 1996, Statoil's Sleipner Vest project (opposite page) has successfully stored 8 million tons of $CO_2$ beneath the North Sea.**

High-temperature gas reactors (HTGRs) may also have a significant bearing on the U.S. nuclear power sector—though the EPRI study did not specifically model them because they don't exclusively reduce electricity $CO_2$ emissions intensity. Operating at much higher temperatures (700º-950ºC) than conventional LWR technology (300ºC), HTGRs can generate both electricity and process heat for industrial processes. As such, they will provide a technology option to reduce $CO_2$ emissions from large consumers of primary energy—chemical refiners, desalinators, etc. The "Next Generation Nuclear Plant" commercial demonstration project—the Department of Energy's (DOE's) application of HTGR technology—is already underway. But significant R&D is necessary to make an HTGR prototype and then have commercial introduction by the mid-2020s.

### Technology Pathway 2: Advanced Coal with $CO_2$ Capture and Storage

*Deployment of commercial-scale coal-based generation units operating with 90 percent $CO_2$ capture and development of ways to transport and sequester the captured $CO_2$.*

Coal currently accounts for more than half of the electricity generated in the United States—most analyses project it to remain the backbone of U.S. electricity supply through 2050 and beyond. Sustaining coal as a viable option in a carbon-constrained world entails achieving two key objectives: increasing the efficiency and reducing the capital cost of pulverized coal and integrated coal gasification combined-cycle (IGCC) technologies; and bringing carbon capture and storage (CCS) to the point of cost-effective commercialization. Large-scale demonstrations will be necessary to convince private in-

Courtesy: Statoil

AP Images

dustry that technology commercialization is feasible.

Significant efficiency gains for pulverized coal can occur principally by increasing the peak temperatures and pressures of the steam cycle. A 10-percent efficiency gain, for example, translates into a $CO_2$ emissions reduction of 25 percent. To accommodate these higher temperatures and pressures, advanced materials (such as corrosion-resistant nickel alloys) and new boiler and steam turbine designs will be necessary—as will the demonstration of plants that are based on ultra-supercritical steam conditions.

Aggressive RD&D could serve to reduce IGCC capital costs by 30 percent relative to current estimated costs, with efficiencies climbing from 30 percent today to the 45-percent range (with $CO_2$ capture). Technology advances include the development of larger gasifiers, the integration of these gasifiers with combustion turbines, and the use of low-energy-demand oxygen supply technologies, like ion transfer membranes (to separate gases during the gasifying process). Over the longer term, warm-gas cleanup (which enables the system to separate gas contaminants closer to the point of their production, instead of having to cool or superheat the gas) and membrane separation processes for $CO_2$ capture will reduce energy losses in these areas.

The greatest reductions in future U.S. electric sector $CO_2$ emissions are likely to come from applying CCS technologies to nearly all new coal-based power plants coming online as soon as cost-effective $CO_2$ capture and storage are commercially available. Currently, adding $CO_2$ capture, drying, compression, transportation, and storage capabilities to IGCC plant designs would increase the wholesale cost of electricity by 40-50 percent. If membrane technology for separating the $CO_2$ from syngas becomes a robust option, however, it could enable a 50-percent reduction in both capital cost and auxiliary power requirements.

$CO_2$ capture at pulverized coal plants is similarly costly. A 2000 EPRI-DOE study concluded that the energy needed by the monoethanolamine process (the principal capture process currently available) would reduce a generator's net power output by 29 percent and raise the production cost of electricity by 65 percent. Right now, there is extensive research to test and develop better solvents, such as chilled ammonia—this may reduce power output by only 10 percent, with an electricity production cost increase of about 25 percent. The equipment supplier Alstom and EPRI are conducting a 5-megawatt pilot scale test of a chilled ammonia process at We Energies' Pleasant Prairie Power Station.

$CO_2$ sequestration is discussed primarily in terms of storage in geologic formations (saline aquifers, for example). Geologic $CO_2$ storage has been proven effective by nature, as evidenced by the numerous natural underground $CO_2$ reservoirs in Colorado, Utah, and other western states.

Courtesy: General Motors

$CO_2$ also is found in natural gas reservoirs, where is has resided for millions of years. The petroleum industry has substantial experience injecting $CO_2$ into existing fields to enhance oil and gas recovery. [See "Carbon Control," by Dennis Wamsted in November/December 2006 *Electric Perspectives*.] But no one has demonstrated large-scale $CO_2$ injection and storage from electricity generation. The U.S. Department of Energy has launched "Regional Carbon Sequestration Partnerships" to identify suitable geologic formations and conduct pilot projects. [See November/December 2007 *Electric Perspectives*, page 14.]

**Technology Pathway 3: Distribution-Enabled Technologies**

*Deployment of smart distribution grids and communications infrastructures to enable widespread end-use efficiency technologies, distributed generation, and PHEVs.*

In the technology pathway analyses, technologies increasing end-use efficiency provide many of the most cost-effective, near-term options for $CO_2$ emissions reduction. That's because electricity suppliers and users can deploy them faster and at lower cost than capital-intensive supply-side options (such as new central power stations). Distributed energy resources typically

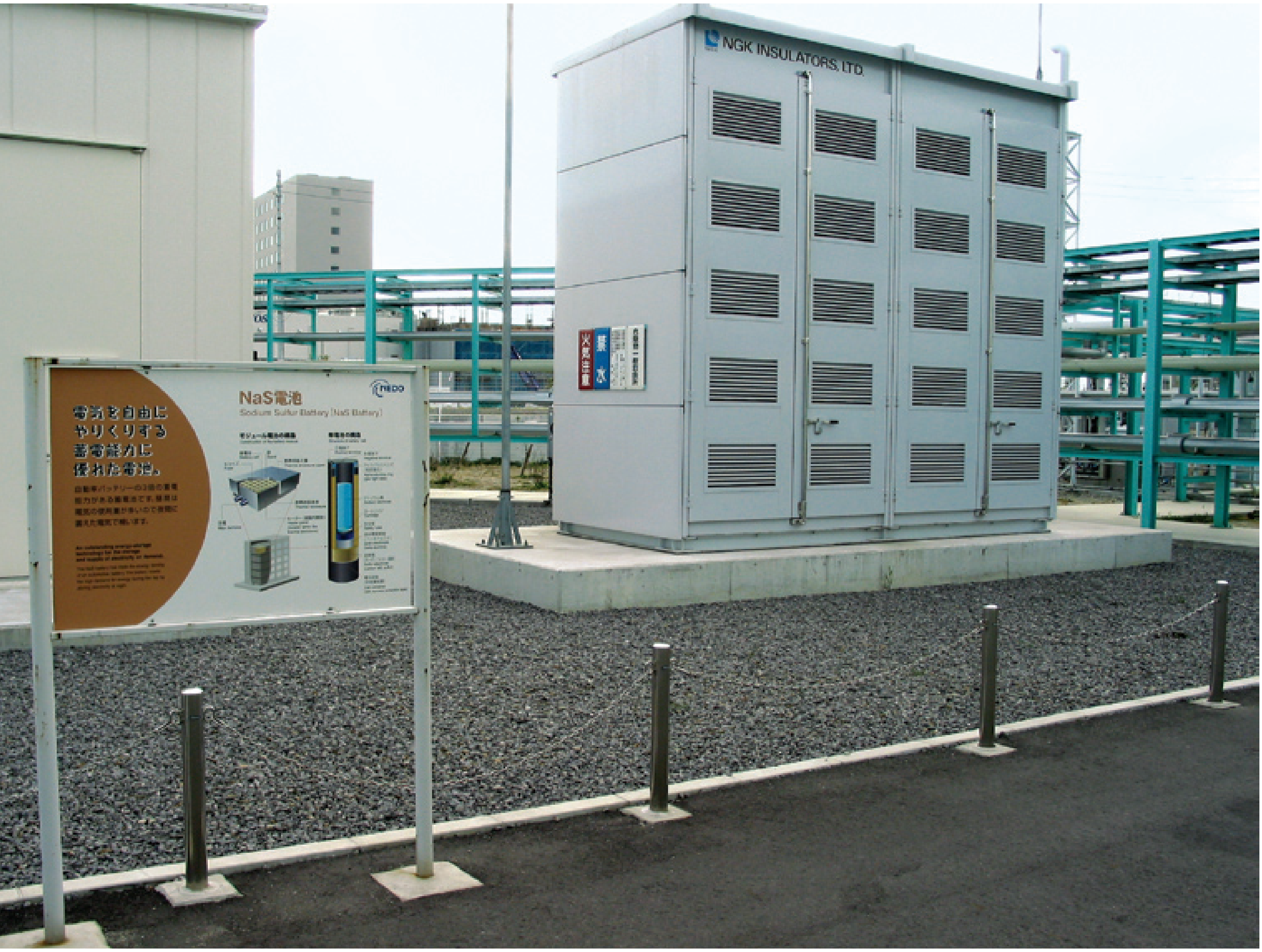
**With a bit more refining, gasifier technology (far left) can turn high-sulfur coals into a cleaner-burning fuel. While still in development, the new Chevy Volt is considered an extended-range electric vehicle as opposed to a hybrid or PHEV. It has an all-electric 161-horsepower, 45-kilowatt motor, capable of moving the car from 0 to 60 in 8.5 seconds.**

Courtesy: Emerson Process Management

Analytical and visualization tools (above) can help operators more accurately forecast renewable energy output and its impact on grid operations. All distributed devices must have high levels of intelligence—computers (inset)—built into their basic operating structure. On the transmission side, advanced energy-storage technologies (page 48) foster reliability improvement, peak-load shaving, and the ability to store energy from renewable sources to supplement nonintermittent generation resources.

have lower $CO_2$ emissions intensities than the coal-dominated mix of central stations. But while active RD&D and commercial development continues for energy-efficient devices and distributed energy resources, their widespread deployment requires a smart, interactive infrastructure, including the ability to integrate new technologies all along the distribution system. Greater penetration of these technologies depends on advances in interoperability standards, advanced metering infrastructure (AMI) capabilities, real-time data acquisition, and dynamic energy management.

Many expect that PHEVs will build on the engineering experience and market acceptance of traditional hybrids, enter the U.S. market around 2010, and gain market penetration through 2050 because of their superior fuel performance and environmental benefits. With parallel advances in smart vehicles and the smart grid, PHEVs could become an integral part of the distribution system itself within 20 years, with their batteries providing electricity storage, emergency supply, and grid stability (the latter also achieved by off-peak charging, which thereby levels load). PHEV research needs include advanced onboard chargers capable of




handling two-way power flow. There also must be demonstrated integration into the smart distribution system to meet peak loads and provide ancillary services (like voltage regulation).

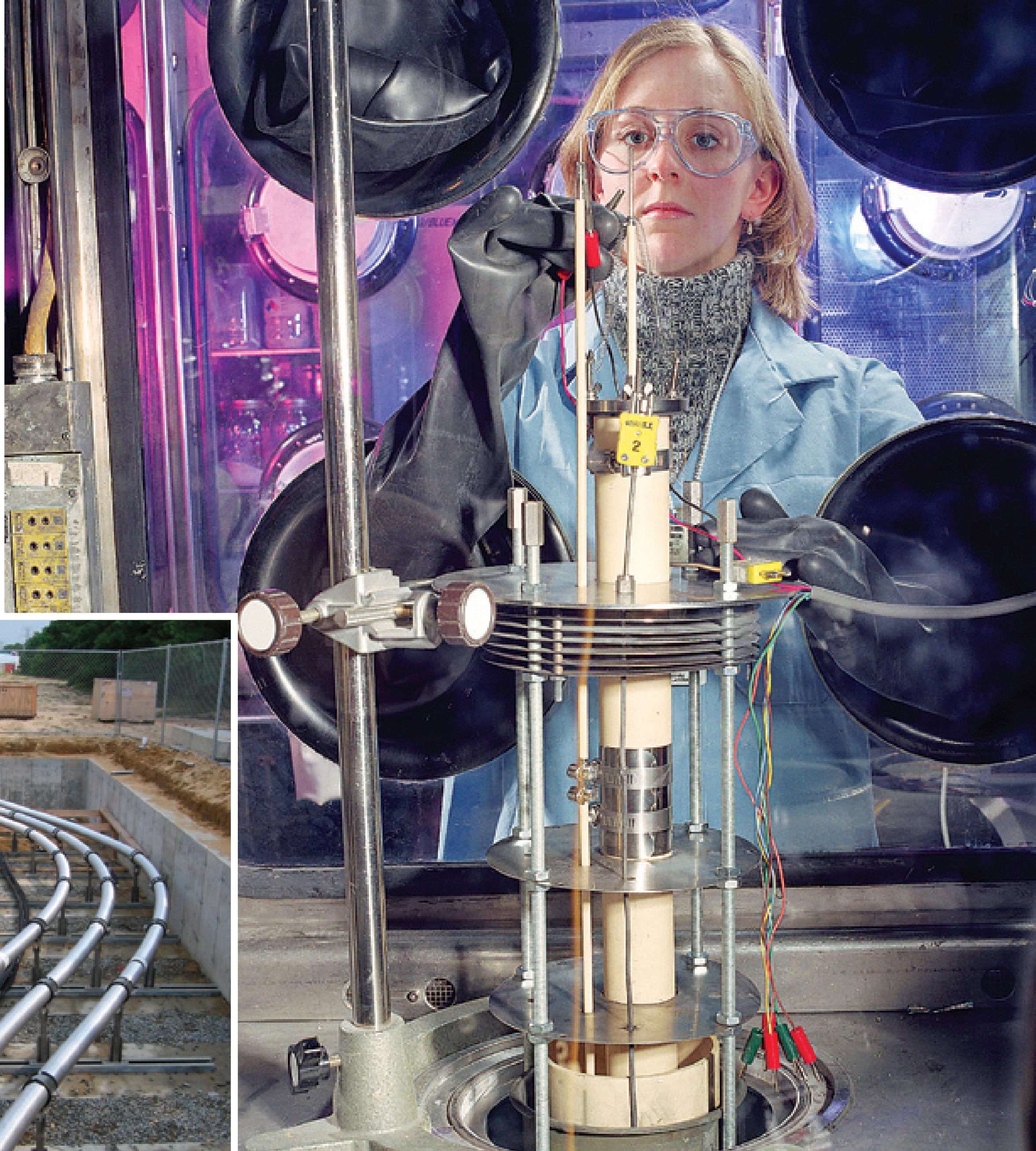
Distribution-enabled technologies such as energy efficient-devices, distributed energy resources, and PHEVs share several common attributes. First, they have or will have high levels of distributed intelligence—computers—built into their basic operating structure, allowing them to become "smart resources" that interact with their digital environment. Second, they incorporate standardized communication protocols, affording high levels of interoperability with other devices through AMI. Third, they are designed to integrate with a smart electricity infrastructure at multiple levels—distribution, energy management systems, and grid operations and planning. These technologies already benefit from RD&D, but transforming the distribution system into a smart enabling infrastructure will also require RD&D efforts into interoperability standards, optimization, and system integration.

### Technology Pathway 4: Transmission-Enabled Technologies

*Deployment of transmission grids and associated energy storage infrastructures with the capacity and reliability to operate with 20-30 percent intermittent renewables in specific regions of the United States.*

Because wind, solar, and many other nonhydroelectric renewable resources are intermittent, integrating them into the transmission system on a large scale will mean significant enhancements to the system itself. These include large-scale energy storage technologies, better grid control tools, and additional transmission infrastructure. The goal is to enable integration of as much as 20-30 percent renewable generation in the overall generation portfolio in specific regions.

Electric energy storage is a critical solution, because it separates intermittent generation from demand. The ability to store energy on a large scale and dispatch it as needed allows intermittent renewable resources to operate




Courtesy: Argonne National Laboratory

Courtesy: American Superconductor Corp.

**High-temperature superconductor wires (HTS, inset) can conduct more than 150 times the power of copper or aluminum wires of the same dimensions, allowing HTS cables to carry more power in existing rights-of-way than conventional cables or overhead lines. EPRI estimates that, for all technologies in the portfolio, the average RD&D expenditure the country must make between now and 2030 is $1.4 billion-$2.0 billion annually.**

during periods of maximum efficiency. Energy storage options such as advanced compressed-air technologies (where the generator pressurizes air in underground storage, to be released later to spin a turbine) and nano-supercapacitors (which combine the high-speed capabilities of capacitors with the energy storage of batteries) could support widespread integration of wind turbines and other renewable energy solutions.

Analytical and visualization tools can help operators more accurately forecast renewable energy output and its impact on grid operations—this provides greater confidence in scheduling adequate capacity to meet energy requirements. In turn, this will help with regulation, reserves, and load-following requirements and facilitate higher penetration of non-emitting resources.

Advanced transmission systems, novel materials, and advanced power electronics can also support increased renewable energy generation. Incorporating superconducting materials into a "supercable," for example, could provide not only a low-loss transmission medium, but also an energy storage medium if the coolant is hydrogen.

### RD&D Funding Needs

All these advanced technologies will require an expanded and multi-decade RD&D program in both the public (government) and private sectors. Advances are needed all along the RD&D chain—basic science, applied research,

**TABLE 1**

**R&D EXPENDITURES REQUIRED**

| | 2005-2009 | 2010-2014 | 2015-2019 | 2020-2024 | 2025-2030 | Average annual (2005-2030) |
|---|---|---|---|---|---|---|
| Distribution-enabled technologies | $250M/yr | $220M/yr | $140M/yr | $240M/yr | $240M/yr | $220M/yr |
| Transmission-enabled technologies | $100M/yr | $130M/yr | $120M/yr | $70M/yr | $60M/yr | $100M/yr |
| Nuclear | $500M/yr | $520M/yr | $370M/yr | $370M/yr | $400M/yr | $430M/yr |
| Advanced coal + $CO_2$ capture/storage | $830M/yr | $800M/yr | $800M/yr | $620M/yr | $400M/yr | $690M/yr |
| Total | $1,700M/yr | $1,700M/yr | $1,400M/yr | $1,300M/yr | $1,100M/yr | $1,400M/yr |

All figures rounded to two significant digits.

development, and demonstration—but large-scale demonstrations will require a significant portion of the funds. (See Table 1.)

The prospect of $CO_2$ emissions policies, coupled with sustained growth in electricity consumption, make it critical for the industry to define priorities and begin RD&D activities. It is highly probable that the strategy for reducing emissions by the electricity sector will be technology-based. This is a sustainable strategy, which minimizes costs to the U.S. economy and creates opportunities for decarbonization beyond the electricity sector and ultimately beyond the United States. It also is clear that no single technology will suffice in meeting $CO_2$ emissions reduction goals—a diverse portfolio of advanced technologies is needed.

Significant RD&D is needed over a sustained period, and given technology development lead times, this RD&D must begin now. The average RD&D expenditure the country must make between now and 2030 is estimated to be $1.4 billion to $2.0 billion annually, but considering that this public and private investment could lower the cost of emissions reductions on the order of $1 trillion, the value of the RD&D investment is clear. ◆