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Energy End-Use Technologies for the 21st Century

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Abstract

The World Energy Council's recent study examined the potential of energy end-use technologies and of research, development, and demonstration (RD&D) into these technologies on a global scale. Surprises are likely, but nevertheless, current research and development offer a picture of what might happen in the future as new technologies face the competition of the marketplace. Given the breadth of energy end-use technologies and the differences between regions and economic conditions, the study focused on technologies that appear most important from today's vantage point. Globally, robust research and development followed by demonstrations of new end-use technologies can potentially save at least 110 EJ/year by 2020 and over 300 EJ/year by 2050. If achieved, this translates to worldwide energy savings of as much as 25% by 2020 and over 40% by 2050, over what may be required without these technologies. It is almost certain that no single technology, or even a small set of technologies, will dominate in meeting the needs of the globe in any foreseeable timeframe.

Absent a significant joint government–industry effort on end-use technology RD&D, the technologies needed will not be ready for the marketplace in the timeframes required with even the most pessimistic scenarios. Based on previous detailed analyses for the United States, an international expenditure of $4 billion per year seems more than justified. The success of new energy end-use technologies depends on new RD&D investments and policy decisions made today. Governments, in close cooperation with industry, must carefully consider RD&D incentives that can help get technologies from the laboratory or test-bed to market.

Any short-term impact areas are likely to benefit from focused RD&D. These include electricity transmission and distribution, distributed electricity production, transportation, the production of paper and pulp, iron and steel, aluminum, cement and chemicals, and information and communication technologies. For long-term impact, significant areas include fuel cells, hydrogen fuel, and integrated multi-task energy systems.

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1 Introduction

The World Energy Council's 2004 study, *Energy End-Use Technologies for the 21st Century*,[8] was aimed at understanding the role that new energy technologies may play in accelerating energy improvements throughout the world—to meet increasingly stringent environmental standards and to broaden the commercial availability of energy and energy services. This study examined the potential of energy end-use technologies and of research, development, and demonstration (RD&D) into these technologies on a global scale. The goals of the study were threefold: to identify important technologies for the next 20–50 years that can increase the benefits of energy; to help define the roles that industry and governments might play in their development; and to determine the investment required to bring these technologies to the stage where the marketplace can decide whether they are useful. This study is believed to be the first attempt to examine the future of energy end-use technologies on a global scale, both geographically and across the energy spectrum. Source and conversion technologies were reported in 2001.[9] While preliminary, these reports should nevertheless encourage industry and governments to undertake more detailed investigations. While surprises are likely, current research developments offer a picture of what may happen in the future as new technologies face the competition of the marketplace.

Energy carriers transmit energy from the source to the end-use technology. Electricity is produced by the conversion of a source, the local choice made based on economic, reliability, convenience, and environmental factors. Gasoline carries energy from petroleum, and sometimes coal. Natural gas is a source that is also an effective carrier and is often used directly with an end-use technology (i.e., conversion to building heat, grid electricity, or transportation power). Coal is more often converted to grid electricity. Solar radiation may be converted directly into low-grade heat. Hydrogen carries energy from fossil sources (oil, coal, or gas), from renewable sources (biomass) or by conversion from any source of electricity. Each conversion step involves cost (energy losses and capital costs for equipment) and therefore affects economics. **Figure 1** is a simplified depiction of the dynamic interplay between energy sources, carriers, and end-use technologies.

Beyond technology, commercialization in the marketplace usually depends on government policies that—at a minimum—do not hinder their introduction, and—at a maximum—may encourage a more rapid and successful introduction.

8. *Energy End-Use Technologies for the 21st Century*, World Energy Council, London, 2004, http://www.worldenergy.org.

9. *Energy Technologies for the Twenty-First Century*, World Energy Council, London, 2001, http://www.worldenergy.org.

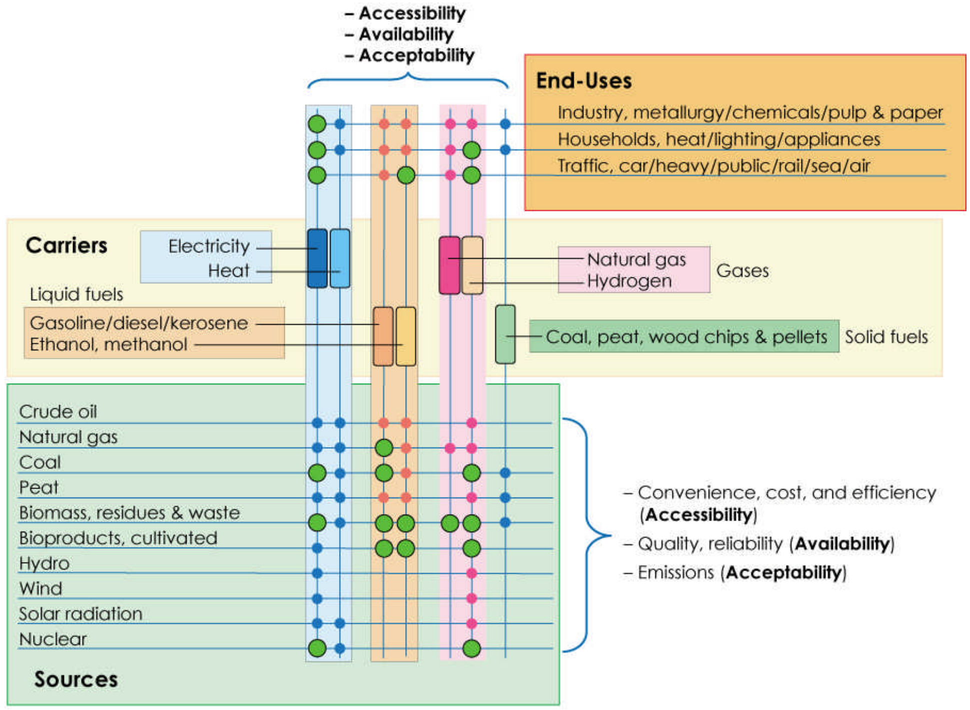

Figure 1. Conversion of energy sources to energy carriers, end-use technologies, and end-uses. Green dots represent intersections where potential gains from RD&D may have the greatest impact on the market for end-use technologies (adapted from Tuomo Suntola, Fortum Corporation, Espoo, Finland, 2003).

One of the most important issues for end-use technologies is their impact on developing countries. Despite advances in science and technology, the absolute economic gap between developing and developed countries is increasing.[10] Clean, abundant water is crucial to the health and well-being of the population and to a vibrant economy. Energy is a prerequisite. Finally, information and communication technologies (I&CTs) take on critical importance in all areas of human life, including energy technologies, but none more important than end-use technologies. I&CTs are a necessary first step in giving people and institutions in developing countries the knowledge to identify and provide energy services.[11]

2 Future Scenarios

The future cannot be predicted and technology breakthroughs as well as surprises are always a reality, yet it is possible using the state of development of the technologies we envision today to look at the historical development of energy technologies and times for technology learning—along with economic considerations, environmental, investment, and other constraints—to gain insights into potential development paths for energy technologies. Earlier

10. The gap appears to be decreasing on a per capita basis, as the two largest population countries, China and India, develop their industrial base. See, for example, *The Economist*, 13–19 March 2004.

11. Useful information on I&CTs may be found on the website of the United Nations Development Program, http://www.choices.undp.org.

studies were updated for this assessment of end-use technologies and scenarios were chosen covering a range of economic and environmental conditions and include the 6 scenarios developed in *Global Energy Perspectives* (GEP)[12] and 28 developed independently for the *Special Report on Emissions Scenarios*.[13]

This study focused on two timeframes: 2020 and 2050. Three extreme scenarios were considered to understand what the high and low demand might be. Two of the scenarios can be characterized as futures of high economic and energy growth as a result of successful globalization efforts (A in GEP, and specifically both A1 and A3, high fossil or low fossil), and the other as ecologically driven with reduced energy consumption due to increased efficiency and energy conservation (C in GEP), specifically C2, which contains nuclear power and renewables. The A and C scenarios represent the effective range of possible futures.

The three scenarios are generally described as follows:

- A1—High-growth scenario that goes beyond conventional wisdom on the availability of oil and gas. No remarkable developments favoring either coal or nuclear. As a result, technological change focuses on tapping the vast potential of conventional and unconventional oil and gas. Oil and gas could be replaced by coal, the gross amounts of energy used staying the same.
- A3—High-growth scenario with transition to post-fossil energy. Large-scale use of renewables with intense biomass utilization and a new generation of nuclear technology. By 2100, nearly equal reliance on nuclear, natural gas, biomass, and wind and solar renewables.
- C2—Reduced energy consumption and unprecedented progressive international cooperation focused explicitly on environmental protection and international equality using nuclear and renewable energy. Technically challenging with a new generation of inherently safe. small-scale nuclear reactors and abundant renewable energy.

Despite enormous differences in energy source assumptions across the scenarios, they share the same assumptions about the availability of fossil- and nuclear-energy resources and renewable-energy potentials. But their deployments differ, depending on assumptions about rates of technological learning, economic development, and other forces. These differences tend to be amplified after 2020. Because of the long lifetimes of infrastructure, power plants, refineries, and other energy investments, there will not be a sufficiently large turnover of such facilities to reveal large differences in the scenarios before 2020.

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12. N. Nakicenovic, A. Grübler, and A. McDonald, Global Energy Perspectives, International Institute for Applied Systems Analysis and World Energy Council, Cambridge, United Kingdom: Cambridge University Press, 1998

13. N. Nakicenovic, et al., Special Report on Emissions Scenarios, A Special Report of Working Group III of the Intergovernmental Panel on Climate Change (IPCC), Cambridge, United Kingdom: Cambridge University Press, 2000

3 General Implications for the Future

In general, the quality of energy end-use services improves across all scenarios to a degree independent of alternative primary energy transitions. Electricity and natural gas are expected to continue to increase within this overall transition toward a more important role for grids, and new energy carriers such as hydrogen become ever more prevalent only toward the end of the century. The role of liquids stays roughly the same with a gradual transition toward synfuels, such as methanol, diesel or gasoline from coal, and ethanol from biomass. The most striking of all transitions is the radical decline in the use of solids. This leads to an important reduction of adverse environmental and health impacts. Solids are increasingly converted to electricity, energy gases, and liquids.

In summary, key technologies are those that improve energy efficiency, renewable energy, and the next generation of fossil and nuclear energy. RD&D carried out now is crucial to the realization of any scenario. Accumulation of experience (technology learning) is vital and this takes time. In the early stages of RD&D programs, cooperation (as between industry and government) is important to ensure interruption-free technological progress with minimal redundancies. Gases—first natural gas and then hydrogen—gradually replace solid and liquid fuels. Hydrogen, while making significant inroads before 2050, predominates only after. A principal reason is that natural-gas conversion and utilization technologies are already well advanced.

4 End-Use Technologies

4.1 Industry

Currently, industry consumes 30% of the world's energy. The A and C scenarios indicate an industry sector worldwide using 165 to 285 EJ per year in 2050 compared with approximately 115 EJ today, a 143% to 250% increase. The energy savings due to new technologies, estimated by taking the difference between A and the C (technologically challenging) scenarios can be as much as 120 EJ per year by 2050, with over 80% likely in Asia. The energy-intensive industries paper and pulp, iron and steel, aluminum, cement, and chemicals are emphasized because together they are responsible for the vast majority of global energy consumption by industry. Emphasis is also given to the service industry because of its increasing economic importance, both to developed countries and to countries in transition.

Most energy-intensive industries implement complex processes having long economic lifetimes and requiring large capital investments. Process changes in such industries are rarely done for energy efficiency alone and new energy technologies only come into play either when a major capital change is done for reasons such as market changes or when new plants are constructed. A consequence is that newly industrialized countries often have more modern and energy-efficient plants than traditional production countries. For example, the steel industry in South Korea has far lower energy intensity than the U.S. steel industry. The largest share of work in the service industries consists of office work using computers, copiers, communication equipment, and other appliances. The relationship between development and energy efficiency of computers and office equipment is illustrated in **Figure 2**.

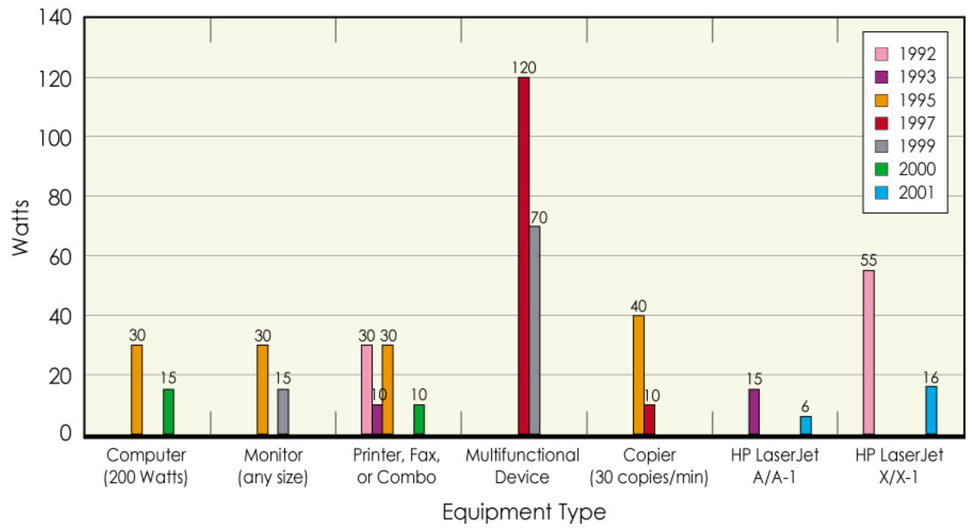

Figure 2. Efficiency as a function of product development [Source: American Electronics Association, Electronic Industries Alliance (EIA), and Information Technology Industry Council (ITI), 2002].

Some important driving forces and areas for technology development are new and profitable products; process integration including heat recovery and co-generation of electricity; efficient use of raw materials including recycling, energy efficiency, and decreased emissions contributing to sustainable development; and decreasing environmental impact of both production processes and product use. Several new electro-technologies have been identified that show promise for the future. Examples are steelmaking with microwaves and ethylene production. There is also ample scope for improvement in energy efficiency in the short term in these industries. Many other studies of industrial energy efficiency point out that there is considerable scope for improvement even with existing technologies.

4.2 Buildings

Currently, buildings consume slightly more than 30% of the world's energy. The A and C scenarios indicate that the buildings sector worldwide may be using between 138 EJ and 229 EJ, a 115% and 190% increase over today. Global energy savings can be as much as 20 EJ/year in 2020 and 90 EJ/year in 2050, with Asia, Europe and North America, being the largest users today, having also the largest potential savings from introducing new technologies.

Residential and commercial buildings typically last for many years—30 to 50 years and some much longer, at least in the developed world. Hence, many of today's buildings will likely still be standing in 2020 and 2050. Parts of buildings may be changed through modifications and retrofitting—improved insulation, new windows and doors—perhaps as often as every 10 or 20 years. However, appliances within the buildings will be replaced at a much higher rate. An important part of buildings of the future are sensors, monitoring systems, and intelligent systems to manage energy use. Thus, the building envelope will adapt automatically to changing needs and conditions (**Figure 3**).

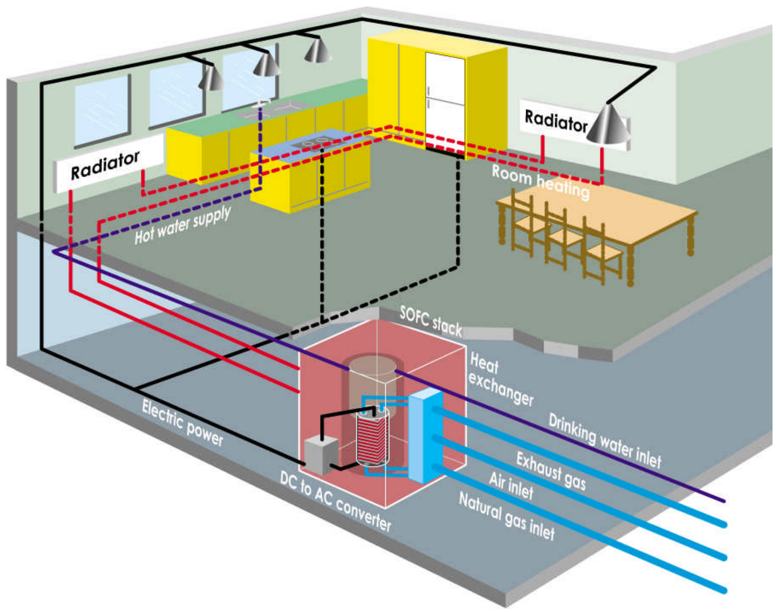

Figure 3. The intelligent house.

It is difficult to draw general conclusions about the energy demand of the developing countries and the potential for savings in their residential buildings because of the wide range of climatic, geographic, and socio-economic conditions. Nevertheless, the majority of inhabitants are poor and are likely to remain so, at least in relative terms, for some time in the future in spite of best efforts to alleviate their poverty. This means that low-cost or zero-cost options for saving energy and improving residential energy use and comfort levels are of critical relevance—equal to improving access to affordable, non-polluting energy sources. While it is often imagined that energy conservation is not immediately important for developing countries, there is convincing evidence that the poor spend a significantly higher percentage of income on energy services than the more wealthy due to lower standards of housing, lack of access to modern energy sources, inefficient conversion devices, and other factors.

Compared with other sectors, the building industry in general is fragmented and performs little of its own RD&D, and as such, depends heavily on government innovations and incentives. The industry is active in demonstrations of technology developed by governments (national laboratories and universities). Furthermore, only international (non-governmental) organizations and only a small portion of private industry study future prospects of this sector in the various regions in the world.

4.3 Transportation

Transportation is a critical end-use sector of energy. It currently uses about 20% of global primary energy (80 EJ/year) and is expected to grow between 150 and 280% by 2050. Energy savings from new technologies can be as much as 105 EJ/year in 2050. The largest savings by region (20% of total) is estimated to take place in the states of the former Soviet Union, with one-half the total achievable by 2030. Transportation provides people with mobility, and because much of the primary energy comes from petroleum, it is the sector most at risk of being disrupted, either by economic conditions or political situations. There is no evidence of saturation in the markets for transportation services in developed countries. When coupled with rapid growth in developing countries, it places emphasis on the future of the transportation end-use sector, assuming that future growth can be supported by national economies.

A closer examination of the three scenarios considered in this study yields an insight into the end-use demand for transportation services worldwide and its prospects. The scenarios project an increase in air and road traffic of close to 200% in the next 50 years. However, although much smaller now, rail and water traffic may grow by more than 500% by 2050 reflecting a much larger population and a drive toward mass transit. Nevertheless, a doubling of the air and road passenger traffic over the next 20–30 years, with two-thirds of all traffic using these means, places a great deal of pressure on automobile and air transport technologies. Not to be overlooked is freight traffic that already accounts for 30–40% of energy use in the transportation end-use sector and is projected to grow by a factor of three over the next 50 years.[14]

Internal combustion engines (ICEs) are being continually improved and they are likely to be the dominant motive force for the next 10 to 15 years, at least. Alternative-fuel vehicles have already penetrated the markets in a small way globally and in major ways in some select markets (Brazil, intra-city buses worldwide). They will likely continue to make inroads for at least the next 50 years, driven by the need to have alternatives to petroleum and aided by advances in ICEs. Hybrid-Electric Vehicles are just beginning to make inroads and will continue to do so, first with mild parallel hybrids and then with more and more powerful electric motors. This technology is also driven by the need to replace scarce petroleum supplies (more crucial in some countries) through both more efficient use and the choice of alternative fuels. Fuel cells, together with hydrogen fuel, while making inroads into markets in the near-term, will have difficulty competing with engines and alternative fuels, often in hybrid vehicles, until enough technological research has been done to enable them to compete. The timeframe for this is likely to be 30–35 years, although with more intensive research this major market penetration could be sooner.

4.4 Crosscutting Technologies

Crosscutting technologies, those that have the potential to broadly and significantly affect the entire end-use of energy, are also important. They may or may not be energy technologies themselves. General crosscutting technologies that have uses more broadly in society are nanotechnology, biotechnology, information technology, and automation and robotics. Perhaps the best example is the fuel cell, an energy technology that may prove useful for both stationary and mobile applications.

When will fuel cells become cost-competitive? The price of fuel cells must drop from the present $10,000 per kilowatt to around $3,000 per kilowatt for remote stationary power, $1,000 per kilowatt for grid-power systems, and $100–300 per kilowatt for automobiles. Utility generation systems now cost up to $2,000–3,000 per kilowatt.

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14. L. Schipper, C. Marie-Lilliu, and G. Lewis-Davis, *Rapid Motorization in the Largest Countries of Asia: Implication for Oil, Carbon Dioxide and Transportation*, http://www.iea.org/pubs/free/articles/schipper/rapmot.htm.

Electricity and natural-gas transmission and distribution (T&D) technologies are the means by which the benefits of energy are made available to customers, the end-users of energy. T&D losses account for 7.4% of electricity consumption in OECD countries and 13.4% in developing countries. Despite the promise of the future of power delivery technologies, the current reality is that delivery systems throughout the developed world cannot satisfy the increasing complexity of the market place or the increasing digital needs of the 21st century. Meeting the requirements of the future will require substantial upgrades in three broad categories:

- load growth and replacement of aging assets;
- reliability of the power delivery system with additional investment needed to make up for reduced expenditures in recent years;
- smart power systems with greater functionality for consumers and the ability to reliably support the digital society.

Advanced energy-storage systems are critical to the long-term deployment of intermittent (renewable) energy supply technologies. These include mechanical (flywheels, pneumatic), electrochemical (advanced batteries, reversible fuel cells, hydrogen), purely electric or magnetic (ultracapacitors, superconducting magnetic storage), pumped-water (hydro) storage, and compressed-gas (air) storage. The various demands for energy storage shown in **Figure 4** illustrate the complexity of requirements for energy storage for a variety of purposes. General goals for energy storage are high reliability, over 85% efficiency, and per-kilowatt costs less than or equal to those of new power generation ($400–600 per kilowatt).

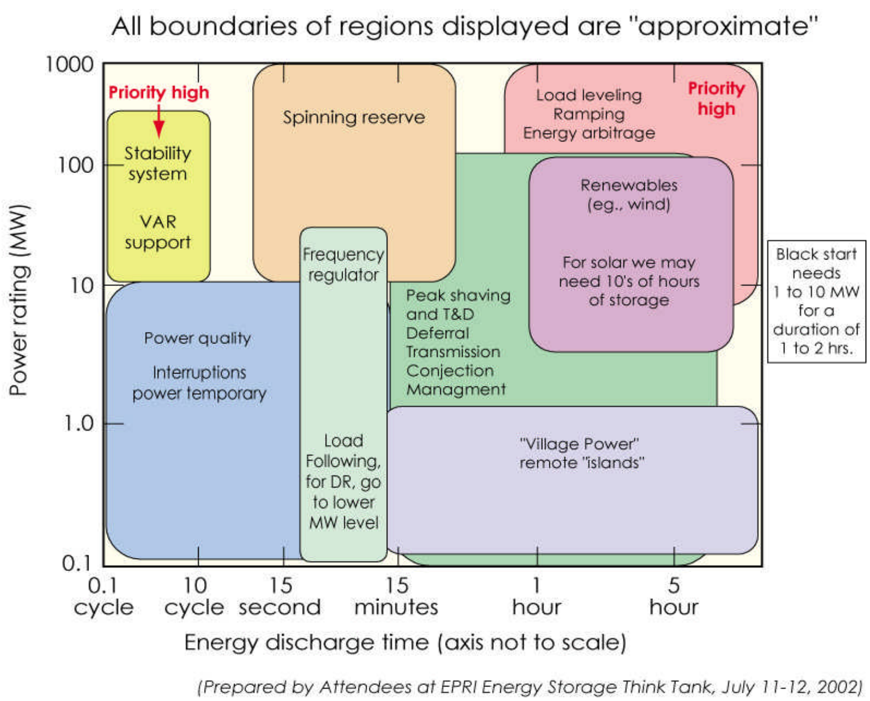

Figure 4. Power and discharge time requirements for energy-storage systems. Highest priority items are marked as is the startup from a complete system blackout. All boundaries of regions displayed are approximate (from Electric Power Research Institute, 2002).

Advances in nanomaterials are expected to be especially valuable in power system applications, from superstrong metal alloys for rotating machinery to tough composites that resist corrosion attack, less-brittle ceramics for power line insulators, and slick coatings that will reduce biofouling in cooling water intakes. Advanced nanostructural catalysts may allow hydrocarbon reforming at very low temperatures (below 100ºC). Successful development of such catalysts would help substantially in making fuel cells that operate at ambient temperatures. Hybrid photovoltaic (PV) solar cells based on conducting polymers and semiconductor nanorods also hold promise; by combining the excellent electronic properties of inorganic semiconductors with the process flexibility of organic polymers, researchers are homing in on PV devices with good efficiencies that are easier and much less expensive to manufacture than conventional solar cells.

Biotechnology includes a particularly rich sub-discipline known as *biomimesis*—the imitation of natural material and process designs in the engineering of man-made structures and processes. Biomimetic materials, typically offering superior properties and functionality, hold tremendous potential for improving the capabilities of solar photovoltaic cells, enhancing the photo-decomposition of water, for allowing fuel cells to operate at low temperatures.

Other important crosscutting technologies are electronics and semiconductors, automation for industry, measurement and control technologies (see Figure 2), and modeling and simulations.

5 RD&D Investments Required

The study identified an international global cooperative expenditure on energy end-use technologies of at least $4 billion per year as necessary to develop the technologies discussed here to the point where they are ready for evaluation by the marketplace. This conservative estimate does not include monies for significant demonstration activities. This step is much more expensive, as illustrated by the expense associated with the demonstration of known technologies. Absent these efforts at R&D (and then demonstrations), technologies for energy end-use will not be ready for the marketplace in the timeframes required by even pessimistic scenarios of world economic development.

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