Chapter 8

THE LONGER-TERM AND GLOBAL CONTEXT[1]

8.1 INTRODUCTION

This report has addressed the policies and costs of reducing the growth of energy consumption and associated environmental pollutants in a single nation – the United States. In addition to the report's restricted geographic focus, the time scale of the quantitative analysis is limited to the period between the present and 2020. The issues raised by the report, however, exist in a global context and are shaped by events throughout the world. They also are affected by long-term trends and the long-lasting impacts of near-term investments.

In the near term, the greatest opportunities for cleaner energy lie in energy efficiency on the demand side and switching to less polluting fuels and energy conversion technologies on the supply side. Although this conclusion is apparent from the CEF analysis of the United States, it is equally true for other countries throughout the world. The remarkable achievement of China in reducing coal production by 250 million tonnes per year in the past two years is an example of the ability of international capabilities to reduce local pollutant and greenhouse gas emissions in the near term (Sinton and Fridley, 2000).

In the longer term, however, the opportunities for a clean energy future depend critically on technologies that do not presently exist in the marketplace or are in early stages of commercial trial. The commercial success of these technologies – which range from technologies that produce energy with low or zero pollutant emissions (renewable, hydrogen, and advanced nuclear power systems) to those that dramatically reduce energy use per activity or output (e.g., 100 mile per gallon automobiles and 200 lumen per watt lighting systems) to systems for the sequestration of carbon – will make the difference between energy futures with high or low economic, social, and environmental impacts.

To address these long-term and global issues, this chapter covers the following topcis. Section 8.2 describes the longer term and global context. Section 8.3 explains the importance of R&D for the long term. Sections 8.4 through 8.7 describe new technologies for energy efficiency, clean energy supply, carbon sequestration, and multi-purpose or crosscutting applications, respectively. In Section 8.8, we provide conclusions relating to energy technologies for global markets in the long-term.

8.2 THE GLOBAL CONTEXT TO 2050

Many of the issues addressed in this CEF report at the national level are at least as prominent at the international level. As the recent PCAST report on international energy innovation states, "The problems and opportunities related to oil, energy-technology markets, nuclear proliferation, climate change, and development/security interactions are all inherently global" (PCAST, 1999).

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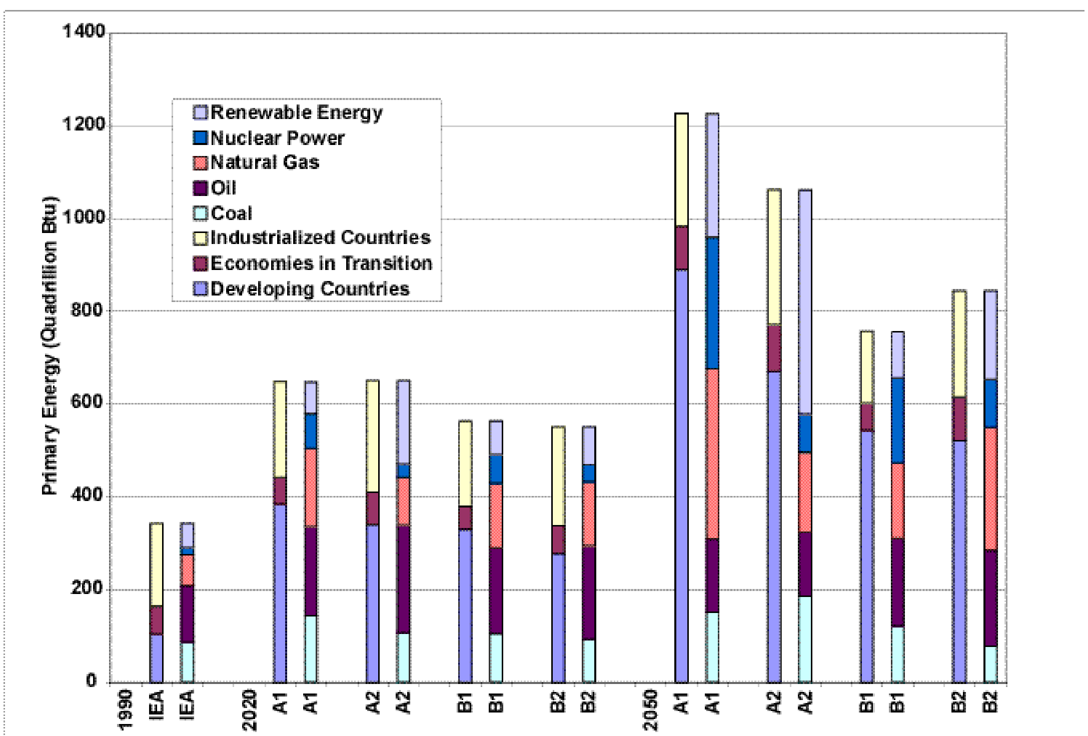
While the U.S. has made huge strides towards reducing its local air pollution problems, internationally the health impacts of local air pollution are staggering and growing as urban populations swell. Many countries do not have access to or cannot afford the SO_x and NO_x control technologies, cleaner natural gas fuels, and low-sulfur coal available to the U.S. The same PCAST study states, "acceptable outcomes all require major innovations in energy technology in order to … lower the emissions intensity of energy supply with respect to greenhouse gases, particulate matter, and gaseous precursors of regional smogs, hazes, and acid deposition (SO_x, NO_x, hydrocarbons)" (PCAST, 1999).

These local pollution problems prevalent around the globe will only worsen as the third of the world's population currently without commercial energy services increase their demand for electricity and access to fossil fuels for heating, transportation, and industrial processes. This growing demand on international fossil fuel supplies will produce higher prices if not outright conflict over access to oil and gas resources.

Figure 8.1 provides a snapshot of results of the major scenario construction and modeling efforts underway in many nations aimed at describing and understanding plausible global energy futures. These four scenarios are the four cases that the Intergovernmental Panel on Climate Change is using to depict a range of likely energy futures (IPCC, 2000). They are the four "marker" scenarios that typify outcomes of the following cases: high world economic growth, low population projections (A1), low economic growth, high population projections (A2), mid-range economic growth, low population growth (B1), similar to B1 but with somewhat lower economic and higher population growth (B2). The income disparity between the wealthy and poor nations was assumed to be considerably reduced from today's levels in all cases except B2.

Fig. 8.1 Four "Marker" Scenarios of Global Energy



The most striking observation from Fig. 8.1 is the tremendous growth of energy demand in the developing world *in all four cases.* The fraction of energy use in developing countries increases from about 30% at present to 50-59% in 2020 and to 62-73% in 2050. (A1 and B1 are at the high end of the range; A2 and B2, at the low.) More remarkably, for three of the four scenarios (A1, B1, and B2) more than 90% of energy demand growth between the present and 2050 occurs in the developing world. For A2, more than 75% of energy demand growth is in the developing world during this time period to 2050. In short, if one is to address the global problems of increasing energy demand, it is clear that the developing world is of the highest priority. From a business perspective, this is where the markets for energy will be. From an environmental perspective, it is where the greatest challenges to preserve and protect the environment from energy-related environmental insults will occur. From a social perspective, it is where low-cost, low-polluting efficient energy technologies will produce the greatest benefits to the largest populations.

These observations should not cause one to underestimate the enormous needs for the industrialized world to place great emphasis on clean energy including implementation of near-term technologies and R&D for the longer term. As will be clear in later section of this chapter, many of the best technologies will be developed and applied in industrialized countries. Developing nations will be reluctant to apply clean energy technologies on a large scale until the technologies have been clearly demonstrated to be technically successful and cost-effective. Such demonstrations will depend on widespread adoption of the technologies in the industrialized countries.

A second observation from Fig. 8.1 is that in all of these scenarios energy demand continues to grow. By 2050, energy demand is 2.2 (scenario B1) to 3.6 (scenario A1) times current levels. A major reason for the increasing energy demand in all cases is that none of these cases involve policies designed to expand energy technology R&D or to alter the choice of energy technology. The four scenarios involve different assumptions about economic and population growth and income distribution.

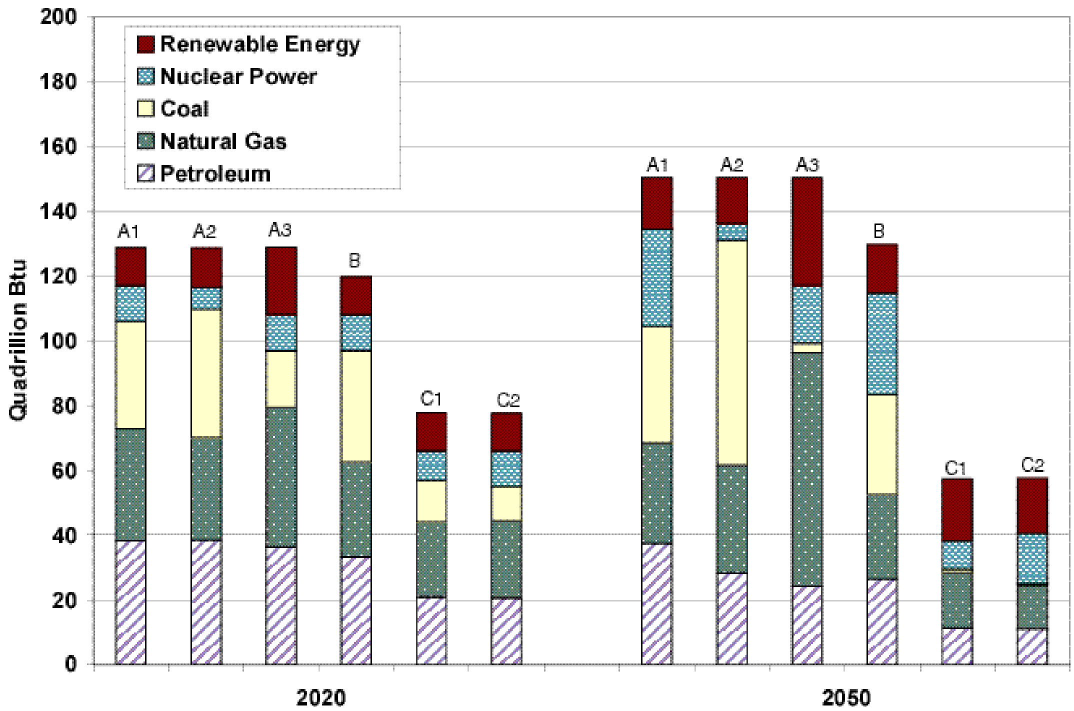
In Fig. 8.2, we present results for the North American region for six scenarios developed by Nakicenovic, Grubler, and McDonald (1998) for the World Energy Council (WEC). On a global basis, the first four of the scenarios are similar to the four IPCC scenarios discussed above. Importantly, Fig. 8.2 illustrates two cases (C1 and C2) in which demand growth is much reduced. These six scenarios portray a wide array of global economic conditions and energy developments over the next half-century. They range from a tremendous expansion of coal production to strict limits; from a phase-out of nuclear energy to a substantial increase; and from carbon emissions in 2100 that are only one-third of today's levels to increases by more than a factor of three. Primary energy use and carbon emissions vary tremendously across the six scenarios and across each of the 11 world regions that are modeled, as exemplified below (and in Fig. 8.2) for the North American region (which includes the United States, Canada, Puerto Rico, Virgin Islands, and Guam).

- Carbon emissions grow the fastest in Case A2, with its stepped-up exports of unconventional hydrocarbons and coal-based synfuels. Scenario A3's combination of comparatively high economic growth (1.6% annually, as in all of the "A" cases) and a focus on renewables and nuclear power results in North American carbon emissions dropping back to approximately 1990 levels by 2050. Case A1 has rates of growth of carbon emissions that are in between those of Cases A2 and A3. Its intermediate performance is driven by a strong growth in nuclear power but only modest increases in renewable energy[2].

[2] Primary energy use in North America in all three of the "A" Cases for 2020 is only slightly greater than in the Clean Energy Future Study's BAU forecast. One would expect the "A" Cases to have much higher levels of energy use, since they include Canada while the CEF Study does not. The fact that the "A" Cases are not markedly higher can be explained largely by their assumption of a 1.6% annual economic growth rate, compared with the assumption of a 2.1% GDP growth rate in the CEF scenarios.

- Case B is characterized by more cautious forecasts of economic growth, rates of technological change, and energy availability. This results in carbon emissions in 2020 and 2050 that are somewhat lower than any of the "A" cases.

Fig. 8.2 Primary Energy Use in North America for Six Global Energy Scenarios



- Only in Case C are there substantial reductions in primary energy use and carbon emissions. In this case, ambitious policy measures accelerate energy efficiency improvements and develop and promote environmentally benign, decentralized energy technologies. This case describes a challenging pathway of transition away from the current dominance of fossil sources. In scenario C1, nuclear power proves a transient technology that is eventually phased out entirely by the end of the 21st century. In scenario C2, a new generation of nuclear reactors is developed that is inherently safe and small scale—100 to 300 MWe—and finds widespread social acceptability. By 2020, the primary energy use and carbon emission levels in Case C are well below those of the Advanced scenario, and they continue to decline in subsequent decades. To some extent the lower levels of energy use and carbon emissions in the "C" Cases are due to the assumption of a modest annual economic growth rate (1.1%).

In contrast to the vast differences in primary energy use and carbon emissions across the IIASA/WEC scenarios in 2050, the 2020 Cases retain vestiges of the current system that result in a number of common characteristics and similarities with one another and with the CEF scenarios. For instance, all of the IIASA/WEC scenarios include consistent trends for North America toward increasing reliance on natural gas and significant declines in traditional environmental pollutants. SO_2 emissions decline even in those cases where coal use increases, as a result of increased investments in environmental control technologies. One notable difference in 2020 is the high level of efficiency assumed in the C1 and C2 scenarios, which far surpasses the energy reductions of the other cases and the CEF scenarios. These "C" Cases and the CEF Advanced scenario differ in particular by their reliance on petroleum fuels in 2020. The IIASA analysts assumed that the existence in Case C of explicit policies to support public transportation and the diffusion of new transport technologies including high-speed trains, fuel cells, and electric vehicles (Nakicenovic, Grubler, and McDonald, 1998, pp. 158-159). The result is a significant reduction in petroleum use. Fuel cells also play a major role in the Advanced scenario, but large increases in public transportation and high-speed rail do not. The result is a smaller, but still sizeable reduction in petroleum use in the Advanced scenario.

8.3 R&D OPPORTUNITIES FOR THE LONG TERM

Given the uncertainties associated with long-term global conditions, it is important, as PCAST (1997) argues, for the United States to maintain a mix of clean energy sources and its leadership in the science and technology of energy supply and use. (See the following box.)

To effect a technology-based solution to the nation's energy-related challenges, many promising efficient and clean energy technologies require considerable applied R&D before they are commercially feasible. Still other technologies are only at the conceptual stage but can be developed with further research. The importance of these long-term efforts is highlighted by key emerging technologies that largely fall outside the time frame of the CEF-NEMs analysis. While the specifics of these long-term advancements are not now known, we can nevertheless see trends that will continue to yield energy advancements after 2020. We describe these in three general areas below:

- energy efficiency (Section 8.4)
- clean energy (Section 8.5)
- carbon sequestration (Section 8.6)

PCAST Conclusion

The United States faces major energy-related challenges as it enters the twenty-first century. Our economic well-being depends on reliable, affordable supplies of energy. Our environmental well-being—from improving urban air quality to abating the risk of global warming—requires a mix of energy sources that emits less carbon dioxide and other pollutants than today's mix does. Our national security requires secure supplies of oil or alternatives to it, as well as prevention of nuclear proliferation. And for reasons of economy, environment, security, and stature as a world power alike, *the United States must maintain its leadership in the science and technology of energy supply and use.*

— *Federal Energy Research and Development for the Challenges of the Twenty-first Century* by the President's Committee of Advisors on Science and Technology (PCAST, 1997) Italics added for emphasis.

The potential long-term contribution of four cross-cutting technologies is also described (Section 8.7) These sections describe a wide array of energy solutions and climate change mitigation options. Omitted from this inventory are numerous potential approaches to climate change adaptation. These range from geoengineering methods that reduce the sunlight reaching the earth's surface to fortification of our physical, informational, and institutional infrastructures. Such approaches deserve consideration and R&D alongside the energy opportunities outlined below. This is well beyond the scope of this study, but for a discussion of these options see Wilbanks and Kates (1999).

8.4 ENERGY-EFFICIENCY R&D OPPORTUNITIES

This section provides a sampling of some of the major advances that could occur with a sustained commitment to energy efficiency R&D. Many of these examples are drawn from the "11-lab study" by DOE National Laboratory Directors (1997) and a report by the International Energy Agency (1999).

8.4.1 Buildings

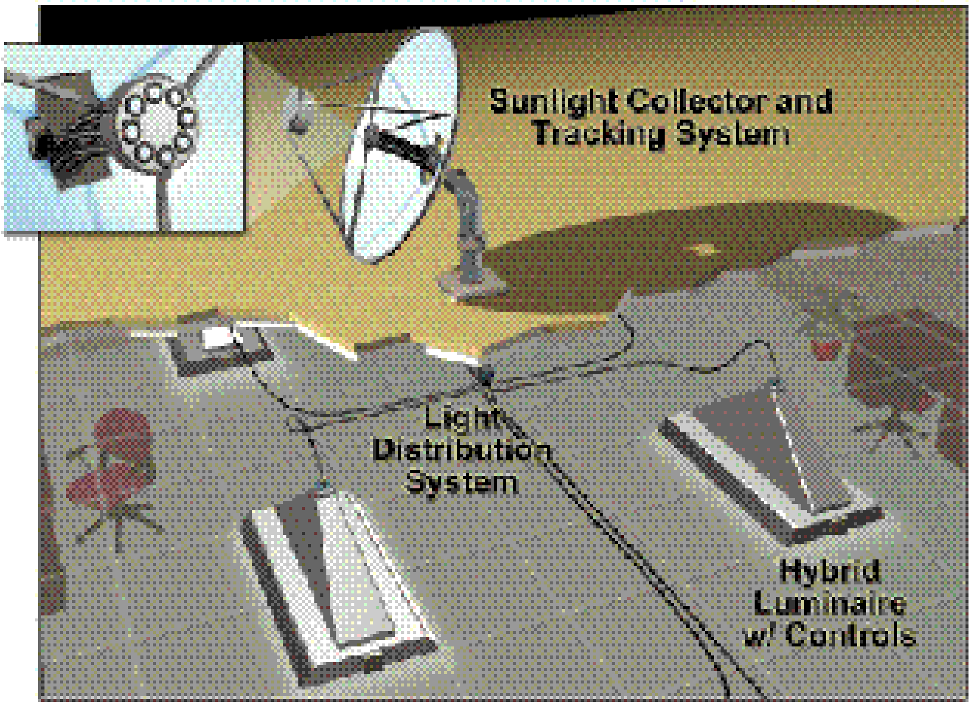
Major transformations are possible in the energy features of buildings as the result of applied technology R&D and in the underlying basic sciences. Inasmuch as most of these are best applied to new construction, their ultimate market penetration will occur well after the 2020 time frame of the CEF scenarios.

Equipment and Appliances. By definition, the energy used in buildings is consumed by equipment that transforms fuel or electricity into end-uses, such as delivered heat or cooling, light, fresh air, vertical transport, cleaning of clothes or dishes, information management, or entertainment. The overall efficiency of this transformation depends largely on the efficiency of the equipment itself.

Numerous opportunities exist to develop equipment that is much more efficient than that currently available.

- It may be possible to virtually eliminate space heating in many climates by means of building shells with very high resistance to heat loss or gain involving high insulation walls, ceilings, and floors and triple pane windows with transparent heat-reflecting films; wide use of passive designs; and mass-produced components (walls, ceilings) with very low infiltration rates.
- Microtechnology could greatly increase heat and mass transfer rates, with highly efficient applications to chemical and thermal systems. One potential buildings application, microheat pumps, could be distributed throughout the building as part of the walls or window. This distributed approach would allow selected rooms or even parts of rooms to be heated or cooled as needed.
- Multi-functional equipment and integrated systems offer the opportunity for a significant increase in efficiency improvement. For example, an integrated water heating/space cooling system that uses heat pumping to meet space heating, air conditioning, and water heating needs could be 70% more efficient than the combined efficiencies of systems in use today.
- Advanced lamp technology integrated with sunlight collectors and daylight distribution systems could be combined with control technologies to reduce lighting energy requirements to a fraction of today's levels. Figure 8.3 portrays a solar lighting and power system of the future. The concept separates and uses different portions of sunlight for two different uses, interior lighting and distributed power generation. The design takes advantage of two facts. First, the luminous efficacy of the visible part of the spectrum is more than double that of electric lamps. Second, photovoltaic cells, especially thermo-photovoltaic cells, are very efficient in converting the infrared portion of the spectrum to electricity.

Fig. 8.3 A Solar Lighting and Power System



- Dramatic declines in the energy consumed by supermarket refrigeration systems could be achieved with distributed system designs. Such systems of the future would locate compressors close to display cabinets thereby avoiding the loss of refrigerant charge. Use of the waste heat by heat pumps for space conditioning would lead to further efficiency gains.
- As energy conversion technologies evolve, many buildings could become net producers of energy as roofs incorporate photovoltaic panels and fuel cells and microturbines generate more power than is required on site. In addition, fuel cells and microturbines produce waste heat that can be employed to serve building thermal loads. These power technologies could transform the entire demand and supply chain in terms of energy generation, distribution, and end-use.
- Building control systems of the future will likely incorporate smart technology to closely match energy and water supply and ambient conditions with the needs of building occupants. Building loads and central plants supplying the loads will be more integrated and optimized to enhance the efficient use the energy streams into and out of the building.

The Building Envelope. The building envelope provides fundamental thermal load control for a building. Walls, roofs, and floors block or delay the flow of heat between a building's interior and exterior. Windows can also block heat flow, provide daylight, transmit solar energy, and provide a view of the outside. High-capacitance internal walls, ceilings, and floors can provide thermal storage that reduces energy use by storing solar energy and reduces peak loads by balancing energy use over a 24-hour period. Improvements in the energy performance of these building elements reduce energy use in buildings and thereby reduce GHG emissions.

Decreasing the building thermal load reduces the need for heating and cooling energy. These emerging building envelope technologies will significantly reduce building energy use:

- super insulation, based on vacuum principles
- new-formula high-efficiency foam insulation that uses no CFCs or hydrochlorofluorocarbons
- advanced gas-filled, multiple-glazing, low-emittance windows and electrochromic glazing
- roof systems that promote self drying, thereby preventing moisture from degrading its insulation
- passive solar components
- durable high-reflectance coatings
- advanced thermal storage materials

Intelligent Building Systems. The process of designing, constructing, starting up, controlling, and maintaining building systems is very complex. If it is done properly, the final product delivers comfort, safety, and a healthy environment and operates efficiently at reasonable cost. If any part of this process breaks down, the product fails to deliver these benefits. The lost health and productivity in office environments alone costs U.S. businesses hundreds of billions of dollars each year. In addition, operating these "broken" systems is estimated to cost at least 30% of commercial building energy use (more than $45 billion). The key to designing and operating buildings efficiently is the ability to manage information, deliver it in a timely manner to the proper audience, and use it effectively for building design and operation. More intelligently designed and operated buildings use energy more efficiently and thus reduce GHG emissions.

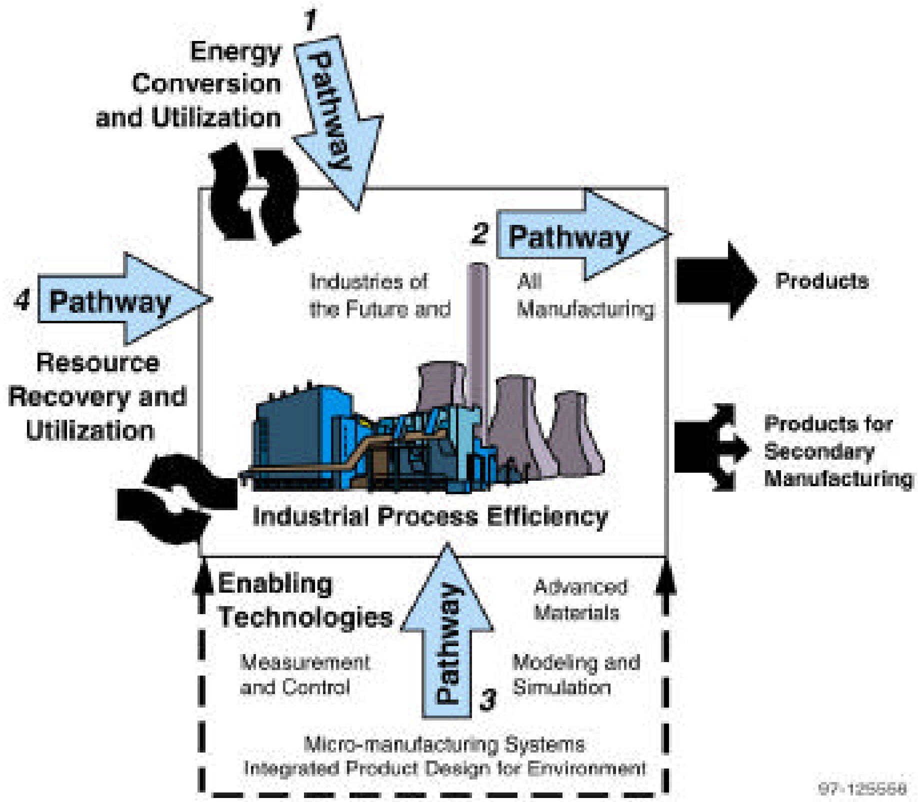
In the intelligent building systems concept, data from the design of the building, together with sensed data, will be used to automatically configure controls and commission (i.e., start up and check out) and operate buildings. Control systems will use advanced, robust techniques based on smaller, cheaper, and more abundant sensors than are in use today. Intelligent devices will use this wealth of data to ensure optimal building performance by continuously controlling and recommissioning building systems using automated tools that detect and diagnose performance anomalies and degradation. Such systems will optimize operation across building systems, inform and implement energy purchasing, guide maintenance activities, and report building performance while ensuring that occupant needs for comfort, health, and safety are met at the lowest possible cost.

8.4.2 Industry

There is, and will long continue to be, opportunities to improve the energy efficiency of specific devices used in industrial applications. There are countless examples: more efficient chemical separations, highly efficient motors, and efficient processes for energy-intensive industries such as iron and steel, aluminum, and cement production. R&D will yield improvements in these areas for years and decades to come.

These are not, however, the ways in which major gains in energy efficiency will come about in industry in the longer term. It has long been recognized that the very substantial gains in energy efficiency result from changes in systems rather than individual devices (Fig. 8.4). The development of advanced control technology – and the application of control technology to industrial systems – has the potential to dramatically reduce industrial energy use.

Fig. 8.4 Four Technology Pathways to Increased Industrial Efficiency
Source: DOE National Laboratory Directors, 1997, p. 2-14



For example, improvements in individual motors can yield efficiency gains of a few percent. In contrast, the redesign of motor systems can produce savings of 20 to 60% (and higher). The addition of variable speed drives for many motor applications can yield further savings. Finally, the integration of advanced sensors and controls enable optimization of the entire system including the motors and the systems that the motors drive (fans, pumps, compressors, etc.). This will make possible the widespread transformation of motor systems. As motors presently consume more than 50% of U.S. electricity, advances in this area have the potential to yield dramatic impacts on industrial energy use.

Reviewing the industrial needs and opportunities that lie ahead, four major technological pathways have been identified. Figure 8.3 illustrates the relationship among them for the industrial sector.

Energy Conversion and Utilization. Energy efficiency could be improved through incorporating the best technologies in a systems approach. Technologies include advanced turbine systems, fuel cells, higher combustion efficiencies, and using thermal energy in a systems approach to mill/plant design. In the longer term, noncombustion technologies are likely to have a significant impact, such as fuel cells and gasification of biomass and in-plant residues. Integrated systems can offer further advantages. Heat cascading, in which the heat output of one process is used as the input to another process (that requires the heat at a lower temperature than the first process), can be shown in principle to yield significant energy savings. Such an approach in practice would mean the co-locating of different industrial processes, equipment design and sizing to permit new types of integration among industrial processes, and the very precise control of liquid and fluid transfers among different industrial processes.

Industrial Process Efficiency. Energy use in industrial processes can be substantially reduced by developing new, more efficient processes as well as by the energy conversion improvements mentioned earlier. These more efficient processes can encourage new, higher-quality products, while generating less waste and fewer undesirable by-products; they also offer the potential for increased economic growth. Technology opportunities for improving process efficiency include more selective catalysts, advanced separations, improved measurement and control systems, improved materials, and improved electric motor systems, such as large motors with superconducting wires. A particularly attractive longer-term opportunity is the use of biotechnology and bioderived materials. Technologies that employ crop and forest materials in the production of chemicals and materials are under development and being pilot tested.

Enabling Technologies. Increased fundamental understanding in chemistry, metallurgy, and biotechnology will allow the development of novel manufacturing processes. This knowledge, along with advanced modeling and simulation, improved industrial materials, and measurements (sensors) and intelligent control systems, will result in major incremental improvements and lead to fundamental break-throughs. Likewise, developing and demonstrating micromanufacturing systems (i.e., mini-mills and micro-chemical reactors) for flexible process configuration and on-site/just-in-place (similar to just-in time) manufacturing can increase energy efficiencies and reduce GHG emissions in the long term. Decentralized manufacturing using locally distributed resources offers the advantage of reduced transport of raw materials and finished goods.

Resource Recovery and Utilization. This technology pathway is built upon the idea of an industrial ecology, wherein a community of producers and consumers perform in a closed system. Fossil energy is conserved and/or energy is obtained from non-GHG sources; in addition, materials are reused or recycled. Through technological advances, the raw materials and resources needed for manufacturing can be obtained by designing products for ease of disassembly and reuse, using more recycled materials in finished goods, and selecting raw materials to eliminate waste discharge or undesirable by-products. Some examples are developing new advanced polymers, composites, fibers, and ceramics engineering through advances in surface techniques and molecular structures. Another approach is to substitute materials such as biomass feedstocks for petroleum feedstocks in producing chemicals. Some longer-term technological approaches will seek to use CO_2 as a feedstock and non-GHG reductants as substitutes for carbon. Such fundamental changes in the way raw materials are obtained, the properties they exhibit, and the way they are used in the design process are likely to yield energy and greenhouse gas savings. Economic success will depend upon industry’s using new design approaches and involving the entire supply chain in thinking about energy reduction in the materials life cycle.

Numerous environmental benefits would result from improved industrial process efficiency and waste minimization. In addition to reduced carbon emissions, these collateral benefits include reduced ground-level ozone, less demand for landfill space, and decreased emissions from incinerators and hazardous waste sites. U.S. industries would also be better prepared to compete in the $400 billion international market for environmental technologies.

8.4.3 Transportation

In the long term, additional advances hold the promise of spectacular reductions in energy use, greenhouse gas emissions, and air pollution from the transportation sector. Opportunities lie in the promise of new, revolutionary propulsion systems and alternative fuels and in the application of information technologies to manage and integrate intermodal transport systems in innovative and more efficient ways. Advances in information technology create new opportunities to increase system-wide efficiency and substitute communication for transportation to enhance economic well being and the overall quality of life.

Hybrid, Electric, and Fuel Cell Vehicles. Developing commercially viable, mass-market electric-drive vehicles (EVs) would free the automobile from dependence on carbon-based liquid fuels while simultaneously reducing vehicular emissions. Hybrid electric vehicles (HEVs) combine an electric drive with an auxiliary power unit and energy storage device (e.g., battery). A heat engine could be used as the auxiliary power source, but if fuel cell technology could be sufficiently advanced and the infrastructure for supplying hydrogen fuel developed, a potentially pollution-free propulsion system would be available (depending upon how the hydrogen is produced).

While HEVs are already on the market, their incremental costs are too high to enable large-scale market penetration. HEVs, EVs, and fuel cell vehicles all face formidable technical hurdles, many of which they share. Developing low-cost, rapidly rechargeable batteries is a critical factor in the success of HEVs and EVs. Fuel cells will also require cost reductions (on the order of 95%) as well as improvements in energy density and reliability. Recent, dramatic progress in batteries and fuel cells suggests that commercially competitive EVs can eventually be developed.

Carbon savings from battery-electric vehicles depend directly on the primary energy sources used to generate electricity. Potential advances in electricity generation technology could make EVs very-low-carbon vehicles. The power plants for HEVs may be fossil-fuel-burning internal combustion engines that could run on alternative fuels or could someday be replaced by fuel cells. In any case, an HEV that is three times more efficient would cut carbon emissions by at least two-thirds. Fuel cells may initially run on gasoline or alcohol fuels (reformed to produce hydrogen) and ultimately could use hydrogen stored on board the vehicle. Which fuels are used and how they are produced will determine the extent of CO_2 reductions over those of conventional vehicles.

Freight Vehicles. Freight vehicles—heavy trucks, railroad locomotives, and ships—are the second largest energy consumers in the transport sector after light-duty vehicles. Heavy trucks and locomotives are almost universally powered by highly efficient (40–45%) diesel power plants. The efficiency of diesel engines could be further improved to 55% by use of such technologies as advanced thermal barrier coatings, high-pressure fuel injection, turbocharging, and reduced-friction and lightweight, high-strength materials. Fuel cells are an especially promising technology for locomotives, where problems of size, fuel storage and reforming are greatly reduced. Emissions of NO_x and particulates remain the greatest barriers to ultrahigh-efficiency diesels, while for fuel cells, cost and the state of development of mobile fuel cell systems present the biggest challenges. Because freight vehicles and their power plants have useful lives measured in decades, the transition to low-carbon technologies would require decades.

Alternative Fuel Vehicles. Alternative transportation fuels are those that require substantial changes in conventional infrastructure, whether in fuel production, distribution, and retailing or in vehicles. Most alternative fuels currently under consideration are being explored for their ability to reduce pollutant emissions or displace petroleum and would have modest GHG reduction potential. Fuels such as compressed natural gas and propane can reduce carbon emissions by 10 to 20%, on a full fuel-cycle basis, over conventional gasoline or diesel fuel.

Far more promising from a GHG reduction perspective are biofuels, such as biodiesel produced from soy or rapeseed oils or ethanol or methanol produced from cellulosic feedstocks. Ethanol from cellulosic feedstocks produce essentially zero carbon emissions over the full fuel cycle. Vehicle technology for using ethanol and biodiesel is at a relatively advanced stage of development. The chief barriers to widespread use of these fuels are cost and limitations on feedstock production.

Air and High-speed Ground Transport. Commercial air travel is the fastest growing energy-using mode of transport. It is also the mode that has achieved the greatest improvements in energy efficiency during the past three decades. Yet commercial air transport is also the most petroleum-dependent mode. Opportunities to replace kerosene jet fuel appear to be many decades away. In the meantime, petroleum displacement in high-speed intercity transport may be achievable by integrating high-speed rail systems with the commercial air network. Operating at 180 to 300 mph, magnetically levitated or steel wheel rail cars could substitute electricity for kerosene in short-distance intercity travel, at the same time relieving both air traffic and highway congestion.

Although air transport has already more than doubled its energy efficiency over the past quarter century, opportunities remain for at least another 50% improvement during the next 25 years. Propfan technology, improved thermodynamic efficiency of turbine engines, hybrid laminar flow control and other aerodynamic improvements, and greater use of lightweight materials could accomplish this 50% improvement, and they are currently under development by NASA and aircraft and engine manufacturers. A potentially important issue for civil aviation is the possible advent of a new generation of far more energy-intensive supersonic high-speed civil transports. The unique requirements of supersonic and hypersonic aircraft could eventually drive the development of alternative fuels for commercial transport.

Having the best and most efficient commercial aircraft technology not only would reduce carbon emissions and petroleum use, but also will be critical to the U.S. aircraft industry's remaining competitive. The principal impediment to continued efficiency improvement and lower carbon emissions is likely to be the relatively low cost of jet fuel, providing an inadequate incentive to adopt new, more complex, and possibly more costly aircraft technology.

Land use and infrastructure investment options offer powerful strategies for reducing the energy- and carbon-intensity of today's transportation sector. Advances in information technology and a variety of policy levers offer the potential to develop urban spatial structures that decrease the demand for travel while maintaining accessibility. The exploding growth of e-commerce and the Internet economy could fundamentally reshape the nation's demand for energy services. On the one hand, Romm, Rosenfeld, and Herrmann (1999, p. 9) argue that e-commerce could lead to significant reductions in the demand for energy services: "The Internet has the ability to turn retail buildings into Web sites and to turn warehouses into better supply chain software, to dematerialize paper and CDs into electrons, and to turn trucks into fiber optic cables." Others argue that the explosion of Internet usage and e-commerce could increase demand for energy services including the transportation of goods and the movement of people. Only time will tell.

8.4.4 Symbiosis of Demand and Supply

While significant energy-efficiency improvements are expected from advancements of energy end-use technology in the demand sectors, additional energy-efficiency improvements are likely to emerge as the delineation between the energy demand and supply sectors vanishes. New competitive market structures are likely to provide energy solutions that seek global optima, in which benefits for both the demand and supply sectors are maximized.

For instance, with the advancements of fuel cell vehicles and their likely market adoption within this decade, it is a possible that residential and small commercial building customers could use their vehicles to produce electricity for their own use or become a net supplier of electric power into the distribution grid. By generating electric power at the location of use transmission and distribution losses can be avoided.

With an advanced information technology infrastructure, distributed generation and load management technologies are likely to become part of the generation mix of the future supply sector. It will then be feasible to trade-off a megawatt hour (MWh) of electric generation with a megawatt hour of load reduction. With such an information technology infrastructure in place, optimal dispatch of generation capacity could be extended to include load management assets at many commercial and industrial customers' sites. Under such a scenario, it is likely that the utilization of less energy-efficient peak power plants could be significantly reduced.

Several other symbiotic energy relations between the supply and the demand sectors are viable. These include district heating and cooling networks and combined heating, cooling and power concepts. Using network concepts, commercial or industrial customers can withdraw energy from or inject energy into the network as needed to maximize their benefits. These flexible energy concepts generally provide much higher efficiencies due to economy of scales and greater controllability.

8.5 CLEAN ENERGY R&D OPPORTUNITIES

8.5.1 Advanced Renewable Energy Technologies

There is considerable opportunity for continued improvement and market penetration of renewable energy technologies after 2020. There are two overarching reasons to believe that renewable energy can continue to evolve and grow as a source of energy not only in the near term, but well through the middle of the next century. First, much of the emergence of renewables will require time as it depends on:

- basic as well as applied research
- learning through increased production over time
- infrastructure development
- technology developments outside of the renewables field itself and the translation of those developments to renewables.

Second, renewables contribute towards the solution of the long-term national issues of climate change mitigation and the economic exhaustion of domestic fossil fuel resources, and towards several nearer term issues like local air pollution, rural development and international economic competitiveness. As these needs become more pronounced, the interest in, commitment to, and development of renewables will accelerate. A level of 20% use in 2025 and greater than 50% use in 2050 is foreseen for the world in a number of energy scenarios from, for example, Shell Petroleum Limited (1996), the World Energy Council (Nakicenovic, Grubler, and McDonald, 1998), and the International Panel on Climate Change (1995). Such high renewables usage will require significant long-term advances, not only in the cost competitiveness of renewables, but also in accessing the renewable resources and identifying new applications of these energy forms.

We examine below the potential for long-term advances in each of the individual renewable energy technologies.

Wind. Due to continuous improvements over the last two decades, wind is one of the renewable energy technologies closest to being economically competitive today. As a result we are seeing significant learning-by-doing at the international level as installations increase and prices fall. In 1999 worldwide wind capacity increased by 36% to 13,400 MW with Germany, the U.S., and Spain contributing over 40% of the increase (EIA, 2000). In the next quarter century, up to 10 to 20% of the electrical capacity in some regions could be from wind power without any adverse operating or economic effects. Such market penetrations require addressing the impact of the intermittent output of wind through modification of systems operation, hybrids with other technologies, energy storage, transmission and infrastructure, and improved wind forecasting.

Fig. 8.5 An Advanced Wind Turbines Design from AWT, Inc.

Improvements will continue in the near term through R&D on higher towers, lightweight blades with advanced airfoil designs, direct drive systems, advanced power conversion devices and development of durable and lightweight structural components. Two major design approaches are being investigated:

- stiff, heavy machines that resist cyclic and extreme loads, typical of historic European technology; and
- lightweight flexible machines that bend and absorb loads.

These options will require some time to sort out and further refine. While these improvements may be refined in the longer term, wind will also benefit for some time from technology advances in other areas. For example, improvements in short-term weather forecasting increase dispatchers' ability to plan for wind generation. Wind will also benefit from a completely restructured electric power system that includes real-time pricing at the retail level. With real-time purchasing, dispatchers will not be as constrained by their day-ahead planning and the intermittency of wind will be less important. Intermittently-available technologies, like wind and photovoltaics, will also benefit from improvements in real-time information control systems for dispatching and metering. Wind at remote resource sites is also likely to benefit from long-term advances in high power electronics and superconducting transmission.

Photovoltaics. About 100 MW of PV modules were sold worldwide in 1997; annual growth has been 15 to 20%. Hundreds of U.S. applications are currently cost-effective for off-grid electric power needs, such as powering remote telecommunications installations and utility sectionalizing switches. International interest is also very high. These off-grid applications are yielding significant improvements in the technology through learning-by-doing. The current annual growth rate of 15 to 20% could easily continue beyond 2020, continually yielding cost and performance improvements.

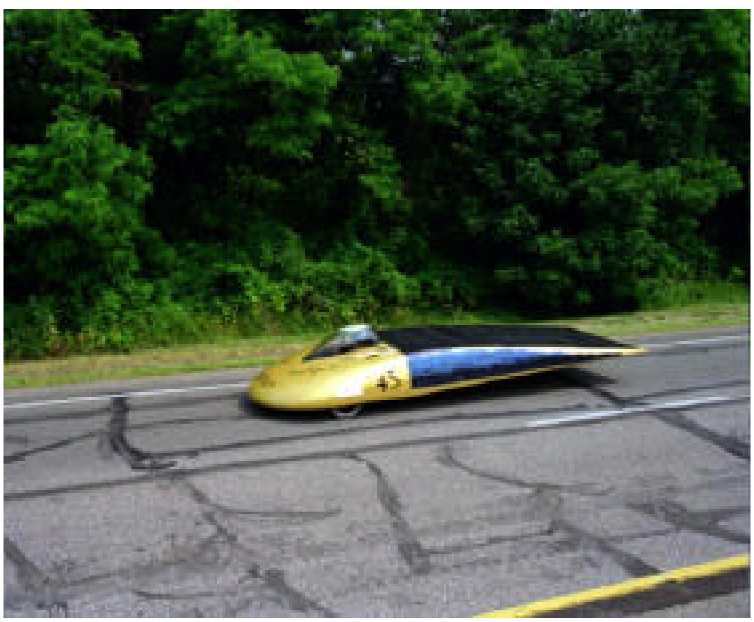
Important RD&D challenges include improving the fundamental understanding of materials and processes to provide a technology base for advanced PV options, optimizing cell and module materials and design, scaling up cells to product size, validating performance in outdoor and accelerated conditions, and improving manufacturing processes. At the same time, basic materials and film deposition research may lead to totally new approaches further out in the future. PV may also benefit over the long term from events as diverse as semiconductor industry advances, artificial photosynthesis breakthroughs, growing demand for personal vehicle transportation in developing countries, and electricity storage advances.

There are also deployment issues that will continue to resolve after 2020. For example, if PV becomes competitive with retail electric rates in the next two decades, we will see substantial installations on buildings. These deployments will be more economic for new buildings where the PV may substitute for roofing or other materials. New buildings also have the advantage that they can be designed and oriented to ensure solar access. Such new-building deployment opportunities could take a century to be fully realized as replacement of the current building stock will extend over the next 100 years.

Electric sector restructuring may also present deployment opportunities that extend well beyond 2020. First, restructuring itself is likely to require some time to be accepted by all the states. Second, aspects of restructuring like retail real-time pricing and net metering that could benefit PV will require some time to be widely accepted. Finally, many consumers will delay investing in distributed technologies like PV until they see clear sustained benefits from all the above factors working together.

In the longer term, PV may also be used to meet the needs of other energy markets. One tantalizing possibility is the light-duty vehicle transportation market (Fig. 8.6). There are several conceivable routes for PV to play a role in this rapidly evolving international market. The most direct possibility is the use of PV either mounted on the surface of a “world car” or stationary applications used to charge the batteries of an electric vehicle. In the long term, PV may also become the major energy source for hydrogen to power fuel cell vehicles. Either electrolysis or some form of direct photoconversion might be used. These concepts are attractive in that they address the long-term issue of petroleum resource availability and because they inherently include storage. They are not hindered by the issue of the intermittent availability of the solar resource.

Fig. 8.6 University of Missouri Entrant in Sunrayce 95



Solar Advanced Photoconversion. This suite of technologies uses the energy of sunlight to directly produce fuels, materials, chemicals, and electricity from renewable sources such as water, CO_2, and nitrogen. Examples of these natural and artificial photosynthesis processes include producing hydrogen from water or biomass and producing biodiesel, methane, and methanol from water, waste, and CO_2. Fundamental advances will be required in multidiscplinary areas involving biological pathways, molecular genetics, natural and artificial photosynthesis, catalysts and catalytic cycles, electron transfer, nanostructures, and materials. Advancements in these areas may yield spin-offs in or benefit from advances in opto-electronics, biosensors, biocomputers, bioelectronics and nano-scale devices.

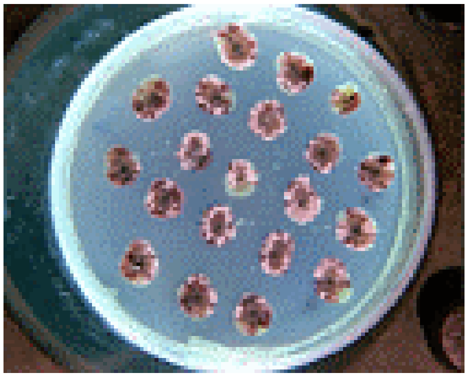
Most of these technologies – involving photobiological, photochemical, and photoelectrochemical approaches – are in the fundamental research stage where technical feasibility must be demonstrated. The pathway to full commercialization will easily extend well beyond the 2020 time frame of our scenarios' quantified results.

Bioenergy. Long-term improvements can be expected in the development of both biomass resources and the conversion technologies required to produce power, fuels and other bio-based products. As molecular genetics matures over the next several decades, its application to biomass energy resources can be expected to significantly improve the economics of all forms of bioenergy. Improvements in economics, in turn, will likely lead to increased efforts to develop new technologies for the integrated production of ethanol, electricity, and chemical products from specialized biomass resources. Similarly, improvements in fuel cells can be expected to increase the value and demand for biogas. At the same time, near-term biomass markets in corn-ethanol and the cofiring of coal-fired power plants are paving the way for the basic infrastructure required for the long-term, and providing opportunities for learning-by-doing.

Biomass gasification has the potential to have a major impact in the forest products industry as existing boilers are replaced. RD&D challenges include resolving issues around ash chemistry and NO_x reduction, demonstrating long-term operation of gas turbines on synthesis gas, improving materials, developing sufficient energy crops for feedstocks, and demonstrating advanced technologies. In the longer-term as fuel cells mature, biomass gasification for use in fuel cells will be demonstrated and will advance in the marketplace.

R&D challenges in the production of biofuels include low-cost production of enzymes, development of microorganisms for consolidated processes, improved performance of thermochemical processing, and advances in producing low-cost energy crops and controlling their composition. Many of these areas will benefit from advances in genetics and biochemistry. One of the most promising approaches today is the hydrolysis of fibrous biomass and subsequent microbial conversion of sugars to ethanol. However, there are other routes that could show future promise (Fig. 8.7). For example, oils can be produced from microalgae by both biological and thermochemical routes. Using the concentrated CO_2 from fossil fuel combustion is one potential route for reducing the cost of producing algae.

Fig. 8.7 Recombinant Streptomyces Bacteria: A Potential Producer of Cellulase



Hydropower. Advanced hydropower technology improves on available techniques for producing hydroelectricity by eliminating adverse environmental impacts and increasing generation and other operational efficiencies. Current technology often has adverse environmental effects, such as fish entrainment and the alteration of downstream water quality and quantity. The goal of advanced hydropower technology is to maximize the use of water for hydroelectric generation while eliminating these adverse effects.

R&D challenges include quantifying the biological response of fish affected by hydropower projects and modeling the forces inside turbines to predict stress levels on fish. Better computational fluid dynamics models may enable the design of "fish friendlier" turbines. The development and demonstration of retrofits technologies is also needed, so that the large number of hydropower plant licenses that are currently scheduled to expire after 2020 are able to take advantage of these advances during the relicensing process. Other long-term opportunities include the integration of hydropower as a storage technology with intermittent renewables. As wind and photovoltaics penetrate the electric markets, hydroelectricity will offer the opportunity to firm up the power provided by these intermittent sources. The energy provided by intermittent renewables can also benefit those hydro sources that are constrained by limited water resources.

Geothermal. Geothermal energy is currently being used to produce power from hydrothermal resources as well as in direct use applications for geothermal heat pumps, greenhouses, and aquaculture. The geothermal resource in the U.S. is huge with over 40,000 Quads of energy potential. However, ninety percent of this potential is at low temperatures (<300˚ F) and much of that is inaccessible for any one of a number of reasons including lack of water, low permeability soils, and environmental concerns. To access these vast, but less attractive resources, basic research is needed in exploration technologies, drilling, reservoir engineering, and conversion technologies. While much technology has been borrowed from the petroleum industry, geothermal resources require new technology for higher temperatures, hard rock drilling, reservoir estimation, fracturing and other geothermal-specific requirements.

By 2020 these efforts could begin to stimulate active interest in enhanced geothermal systems. The use of hot dry rock resources appears particularly promising, where cool water is injected into dry hot rock formations through one well, travels through fractures to another production well, and is pumped out to run a steam turbine and produce electricity. Advances in offshore drilling technology by 2020 may also lead to the development of geopressurized brines in the Gulf of Mexico which provide not only thermal energy, but also associated methane resources and mechanical energy from the great pressures in the resource.

8.5.2 Inherently Safe Nuclear Power

There is strong potential for nuclear power to be a growing contributor to the energy mix of the United States, and the rest of the world, this century. In its 1997 report (PCAST, 1997), the PCAST Energy Research and Development Panel concluded that restoring a viable nuclear energy option to help meet our future energy needs is important. The PCAST Panel further determined that a properly focused R&D effort should be implemented by DOE to address the principal obstacles to achieving this option. These obstacles include issues involving proliferation, economics, nuclear waste, and safety.

In response, the DOE has established several initiatives including the Generation IV Program (to develop advanced nuclear reactor designs) and the Nuclear Energy Research Initiative (NERI, 1999) (to accelerate the long-term advancement of nuclear energy science). These R&D initiatives address both innovative technologies that can be developed and implemented over the next 10 years and revolutionary technologies that can be implemented over the next 30 years. Primary areas of needed research are described below.

Proliferation-Resistant Reactor and Fuel Technologies. Research to reduce or eliminate the potential for proliferation of nuclear fuel materials is critical to the success of nuclear energy systems. The development of new fuel cycles that reduce plutonium buildup, produce less waste, and have the least proliferation potential could significantly strengthen the future viability of nuclear power. New reactor concepts and plant configurations, large and small, that eliminate access to the nuclear fuel also hold great promise.

New High-Efficiency Reactor Designs. Scientific and engineering R&D of new and more efficient nuclear reactor concepts to achieve significant increases in performance and economics are required. Innovative reactor and power conversion concepts are needed that offer the prospects of higher efficiency, improved performance, design simplification, enhanced safety, and low cost. Promising future advances as envisioned in the Generation IV Program include:

- the development of reactor design advancements and alternative reactor core concepts;
- passive safety systems and components;
- innovative reactor concepts for electrical, nonelectrical or cogeneration purposes;
- technologies and design concepts incorporating construction and operations simplicity and cost reduction features; and
- specialized new applications such as process heat and electricity systems to compete in the global market.

Advanced Low Power Reactor Designs and Applications. Accelerated nuclear reactor R&D could produce innovative, small, compact, and easily deployable power reactor designs employing passive safety systems and long life cores for use in developing countries or for specialized applications. Potential applications include electricity generation, process heat, medical isotope production, and nuclear research. The ultimate objective is to develop small reactor systems, primarily for export, that need no on-site refueling for the life of the reactor, employ high safety margins and passive safety features, automated operation, minimized waste production, and high cost effectiveness.

Advanced Nuclear Fuel and New Technologies for Storage of Nuclear Waste. The first half of the next century could see the emergence of innovative technologies and techniques for the on-site and surface storage of commercial spent fuel and high level waste, and implementation of strategies for reductions in high-level waste generation. To achieve this, research is needed in the areas of interim storage and transport, transmutation, separation science, and waste form characteristics and integrity. New and innovative scientific and engineering R&D in advanced nuclear fuels is also necessary to realize measurable improvements in the performance of nuclear fuel with respect to safety, waste production, and economics to enhance the viability of nuclear reactor systems.

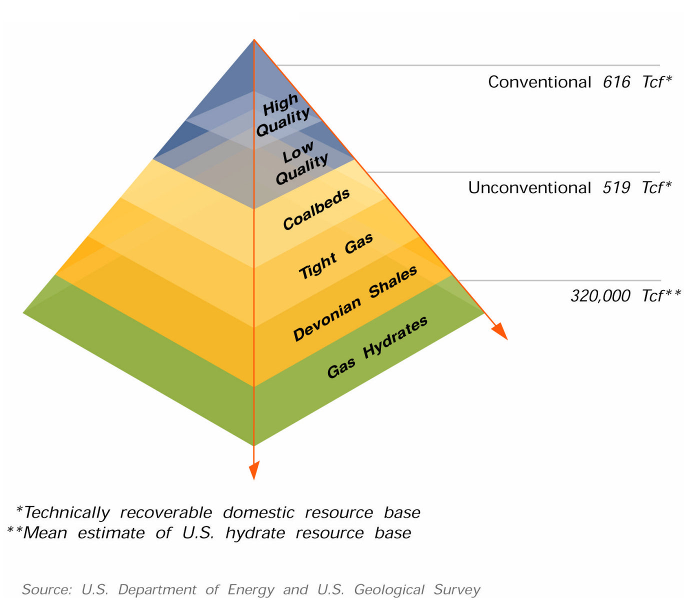
Fusion energy is also an important, albeit long-range element of the nation's energy strategy because of its many potential advantages as an energy resource. These benefits include: an almost limitless supply of fuel (primarily isotopes of hydrogen); greatly reduced radioactivity compared with fission (there are no long-lived gaseous radioactive products); and negligible atmospheric pollution (as with current nuclear generation) compared with fossil fuels. The successful application of practical fusion energy technologies at some point in the 21st century could help to enhance the Nation's energy, provide an environmentally acceptable alternative to fossil-fuel combustion, and help ensure continued economic growth through reliable electricity supply. Nuclear power can play a major role in the future electricity supply if issues described above are successfully addressed.

8.5.3 Fossil Energy Supply

In spite of the heavy dependence on fossil fuels in most parts of the world, the remaining fossil resource is still vast. One of these fuels, natural gas, is becoming increasingly popular because of its clean burning characteristics and relatively low greenhouse gas emissions compared to other fossil fuels. Finding ways to tap less conventional gas resources could extend the world's gas supplies for hundreds of years, as suggested by Fig. 8.8. Unfortunately, a fundamental characteristic of the world's hydrocarbon resources is that the larger the resource, the more challenging and difficult it is to exploit. Long-range targets of particular interest include deep gas and methane hydrates.

Deep Gas. A significant amount of undiscovered domestic gas is in accumulations deeper than 15,000 feet. They are in widely differing geologic settings, including ones shown as unconventional in Fig. 8.8. A number of technology challenges must be overcome to exploit deep resources, including better ways to detect commercial volumes of gas using surface-based sensing, and advanced materials for drilling at high temperatures and pressures at extreme depths.

Fig. 8.8 U. S. Natural Gas Resource Base



Methane Hydrates. Domestic methane hydrates are found on land in permafrost regions (such as much of Alaska) and within ocean floor sediments. To achieve safe and environmentally acceptable production by 2015, it would be necessary to determine the location, sedimentary relationships, and physical characteristics of methane hydrates, and develop production approaches for disassociating the methane from the cage of water ice molecules in the hydrates.

Fig. 8.9 Burning Gas from Methane Hydrate Ice

Source: ORNL Review, 2000, p. 4

8.5.4 Fossil Energy Conversion

Continued improvements in efficiency and environmental acceptability could enable fossil energy to play a growing role in the U.S. and world's energy mix while pursuing the goals of a clean energy future. The DOE has developed a new approach to 21st century energy production from fossil fuel-based systems called the "Vision 21 EnergyPlex, (FETC, 1999)." This vision integrates advanced concepts for high-efficiency power generation and pollution control into a new class of fuel-flexible facilities capable of co-producing electric power, industrial-grade heat, high value fuels, chemicals and hydrogen, with virtually no emissions of air pollutants. This multi-product approach, if successful, will squeeze every useable amount of energy out of a fuel source, achieving efficiencies in the post-2015 period that could approach 60 to 80 percent, well above the typical 33 to 35 percent efficiencies of today's conventional coal-fired power plants.

A *Vision 21* power plant would also have remarkable fuel flexibility. It could be fed by coal, natural gas, biomass, municipal waste, or perhaps a combination of these fuels. Made up of modules that could be interchanged to meet different fuel and product needs, *Vision 21* plants could be tailored for a variety of geographic regions and different energy markets. Advanced technology could permit CO_2, to be captured, and ultimately eliminated when viable sequestration approaches emerge in the next several decades. The Vision 21 plant depicted could be extremely compact and efficient. With near-zero emissions, the plant could have no stack, and in some cases be sited near urban and industrial centers, thereby relieving the need for additional transmission lines.

Many of the initial building blocks for "Vision 21" are already under development. In the future these could be integrated with further advances such as described below.

Fuel-Flexible Gasification. Coal gasification is an ideal core technology for "Vision 21" because it produces a gas stream that can be combusted for electric power, used as a source of hydrogen for a fuel cell or chemical process, or processed as a fuel gas for industrial plants. To enhance fuel flexibility, R&D is needed to determine how best to gasify fuel mixtures, such as coal and biomass or fuel-rich wastes.

Fig. 8.10 Conceptual Drawing of a Vision 21 Energy Plex

Gas Separation Technologies. To make a future "Vision 21" plant as cost-effective and efficient as possible, lower-cost means would be needed to produce oxygen for the gasification process. This need could be met by developing innovative membranes to replace the costly cryogenic air separation used today. Similarly, advanced membranes could offer a better way to separate a pure stream of hydrogen from the gasified hydrocarbon fuel that could then be used by a fuel cell or converted to high value fuels and chemicals. Gas separation technologies could provide an effective future means for separating CO_2 effluents from combustion streams for sequestration in deep aquifers, depleted oil and gas wells, or ocean depths and sediments.

Fuel Cell/Turbine Hybrids. To date, R&D has focused largely on fuel cells and turbines as separate power generating devices, but in the future, combining the two may offer significant efficiency and economic benefits. A key challenge that could be met over the next two decades is the integration of fuel cell and turbine technologies and the adaptation of them to run on multiple types of fuel feedstocks.

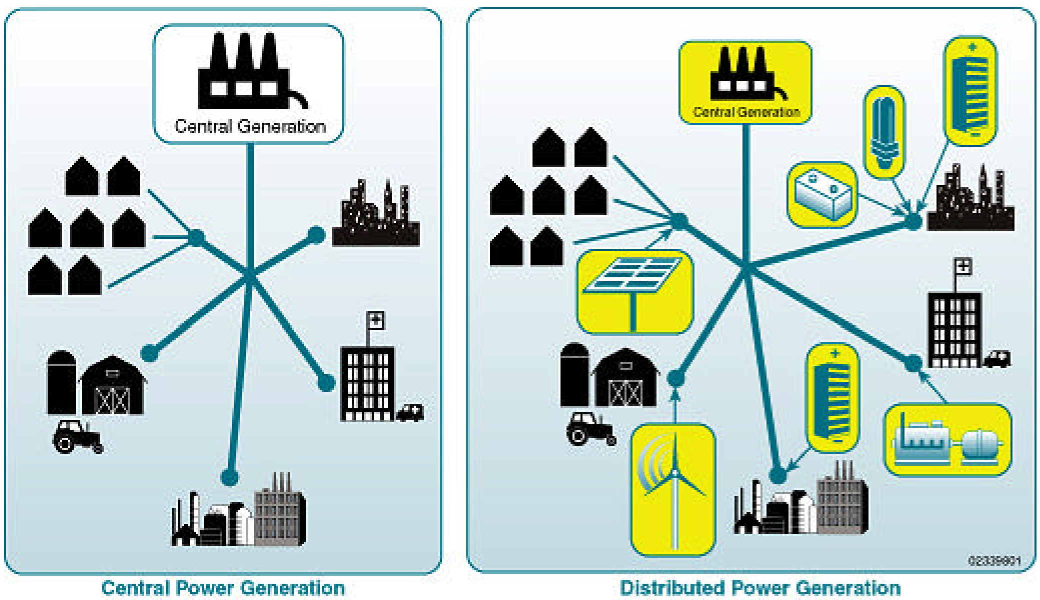
High-Performance Combustion. An alternative "Vision 21" configuration would rely on combustion rather than gasification. In this design, advanced technologies such as pressurized fluidized bed combustion and high-temperature heat exchangers will need to be improved through expanded R&D.

If the "Vision 21" concept can be successfully coupled with low-cost carbon sequestration, the result will be a future energy facility with virtually no environmental impacts outside of its "footprint."

8.5.5 Distributed Energy Resources

Distributed energy resources are small power generation or storage systems located close to the point of use. They offer significant potential for reduced transmission and distribution costs, higher efficiencies through cogeneration, fuel flexibility, reduced emissions of carbon and local air pollutants, enhanced power quality and reliability, and more end user control. Many believe that these potential advantages will bring about a "paradigm shift" in the energy industry, away from central power generation to distributed generation (Fig. 8.11).

Fig. 8.11 The Transition to Distributed Energy Resources



With generation located near loads, transmission and distribution costs could be reduced by (1) deferring upgrades to substations and other transmission and distribution facilities; (2) providing black start capability, spinning reserves, and voltage support; and (3) reducing reactive power losses. Some distributed generation technologies, like renewable energy and fuel cells, can generate electricity with no, or at least fewer, emissions than central station fossil-fired power plants. Total emissions can also be reduced through distributed generation using fuel cells, microturbines and internal combustion engines if the waste heat generated is usefully employed on site to improve overall system efficiency. Finally, as the electric industry restructures, distributed generation could also provide increased reliability as reserve margins shrink, independent system operators become effective in their operation, and market volatility is tamed (NRECA, 2000).

Today's distributed generation market in the United States is largely limited to backup generation. Customers are hospitals, industrial plants, Internet server hubs, and other businesses that have high costs associated with power outages. Smaller niche markets are growing, where distributed energy resources are used as a stand-alone power source for remote sites, to reduce costs associated with on-peak electricity charges and price spikes, and to take advantage of cogeneration efficiencies. Distributed generation could be particularly advantageous in developing countries by requiring less infrastructure investment, reducing transmission line requirements, and being more responsive to rapidly growing demand for power. It is likely that this increased demand will continue, and possibly accelerate, well into the future as small-scale modular units improve in performance and decrease in cost, interconnection and other barriers are tackled, the demand for electricity continues to grow, and the worldwide digital economy explodes.

A recent report commissioned by E Source describes a visioning process based on the assumption that the demand for ultra-reliable power service will increase far more rapidly than the demand for electricity itself (Geraghty, 1999). Many futurists foresee more and more digital information being created, processed, and transported faster and faster by power-sensitive equipment. Power densities of micro-processors and routers are increasing, as are the requirements for heat dissipation associated with this equipment. This growth could mean an increase in the cost of power outages and a growing demand for power reliability. This indicates a rapidly growing demand for ultra-reliable power services, which could be met by distributed energy resources.

Research is ongoing now on distributed generation technologies and their interconnection to the grid. For distributed generation to enhance system-level efficiency, improvements would be needed in the performance of power-producing equipment such as advanced turbines and microturbines, natural gas engines, fuel cells, cooling heating and power systems, and renewable and hybrid systems. A next generation of power electronics, energy storage, and sensors and controls would also be required. With successful RD&D, the United States (and much of the rest of the world) could realize a paradigm shift to ultra-high efficiency, ultra-low emission, fuel-flexible, and cost-competitive distributed generation technologies easily interconnected into the Nation's energy infrastructure and operated in an optimized manner to maximize value to users and energy suppliers, while protecting the environment.

8.6 CARBON SEQUESTRATION R&D OPPORTUNITIES

There are numerous ways of removing CO_2 from the atmosphere and storing it or keeping anthropogenic carbon emissions from reaching the atmosphere. Six of these carbon sequestration methods are described in a recent report (DOE, 1999):

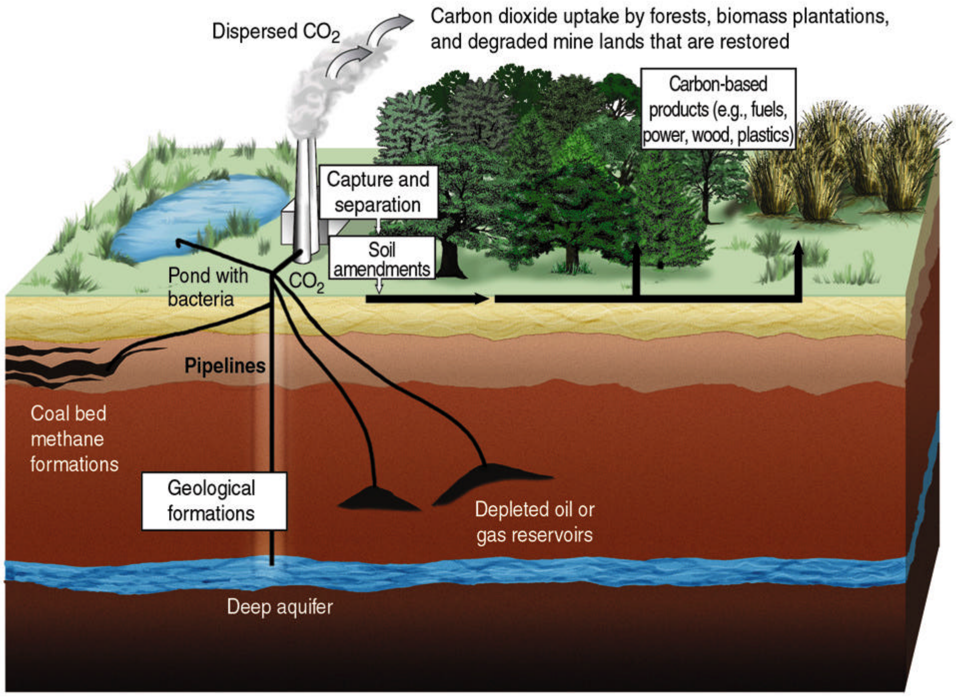
- Separation and capture of CO_2 from the energy system
- Sequestration in the oceans
- Sequestration in terrestrial ecosystems
- Sequestration in geological formations
- Advanced biological processes
- Advanced chemical approaches

Some of these options are available today – such as improved agricultural practices and wetlands protection. Others are available in the near-term because they can provide important secondary benefits, such as improving ecosystems during reforestation and enhancing oil recovery through CO_2 injection. Most, however, are long-term carbon management options that require considerable research to ensure their successful development and acceptance. Ultimately, one can envision a systems approach to carbon management, involving a combination of carbon capture, separation, and sequestration (Fig. 8.12).

Separation and Capture of CO_2 from the Energy System

Several currently available technologies could be used to separate and capture CO_2 from fossil-fueled power plant flue gases; from the effluents of industrial processes such as iron, steel, and cement production; and from hydrogen production by reforming of natural gas. CO_2 could be absorbed from gas streams by contact with amine-based solvents or cold methanol. It could be removed by adsorption on activated carbon or other materials or by passing the gas stream through special membranes. Commercial hydrogen production via reforming of natural gas involves separating H_2 from the reformate gases (a mixture of unreacted methane and other hydrocarbons, CO, CO_2, and water) by adsorption processes such as pressure swing adsorption (PSA). Should fuels decarbonization (e.g., reforming of natural gas to produce H_2) become part of a CO_2 mitigation strategy, the PSA technology could logically be extended to CO_2 separation and capture.

Fig. 8.12 Schematic of an Integrated System with Carbon Capture, Separation, and Sequestration



Source: ORNL Review, 2000, p.13.

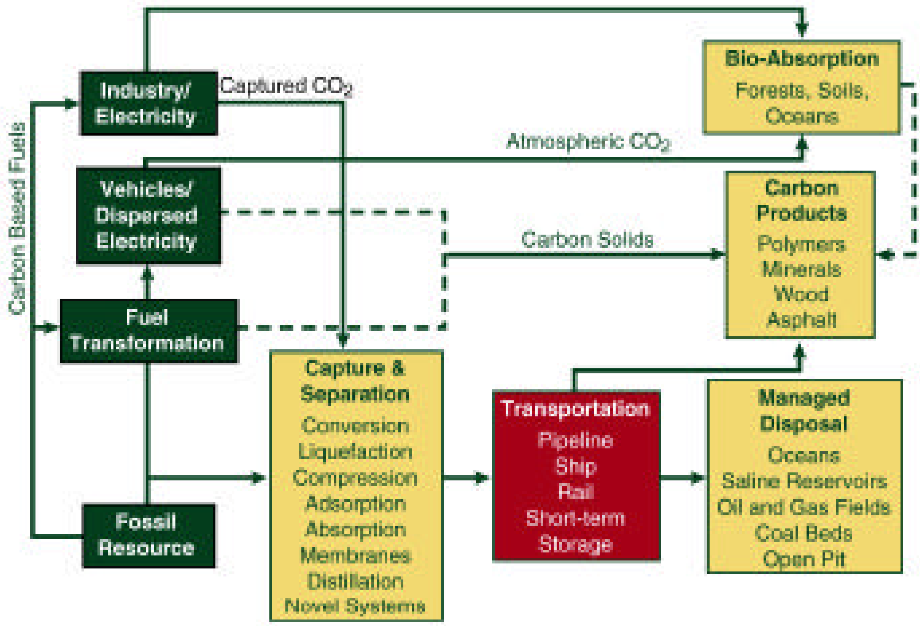
Advanced methods might include adsorbing CO_2 on zeolites or carbon-bonded activated carbon fibers and separating it from flue gases or process gases from industrial operations using inorganic membranes. The use of commercial CO_2-removing processes that scrub gases with amine-based solvents is projected to raise substantially the cost of producing electrical power from coal-fired power plants using existing technology. Thus although CO_2 is separated routinely, dramatic improvements would be necessary to make the process economical. Techniques would be needed to transform the captured CO_2 into materials that (1) could be economically and safely transported and sequestered for a long time or (2) could be used to make commercial products (e.g., construction materials) that could offset the costs of separation and capture.

There are numerous options for the separation and capture of CO_2, and many of these are commercially available. However, none has been applied at the scale required as part of a CO_2 emissions mitigation strategy, nor has any method been demonstrated for all the major anthropogenic sources. Many issues remain regarding the ability to separate and capture CO_2 from anthropogenic sources on the scale required, and to meet the cost, safety, and environmental requirements for separation and capture.

Geologic or ocean storage sequestration options that use a concentrated source of CO_2 require low-cost carbon separation and capture techniques to be viable options. The scale of the industrial system required to process gigatonnes of carbon warrants investigation into new solvents, adsorbents, and membrane separation devices for either pre- or post-combustion separation.

Figure 8.13 gives a top-level picture of a carbon capture and sequestration system and its linkages to the energy system. Within the current fossil energy system, carbon is processed in several forms by different fossil fuel technologies in many different parts of the energy system. To keep it from being emitted to the atmosphere, this carbon must be captured, processed in some way to separate or purify it, and changed to a solid, liquid, or gaseous form that is convenient for transport. It can then be transported in an engineered system to a site for sequestration or for transformation into a long-lived end product. Alternatively, the carbon could be emitted as CO_2 and transmitted through the atmosphere if sequestration by bio-absorption could be assured in some part of the natural carbon cycle.

Fig. 8.13 A Carbon Capture and Sequestration Technology System



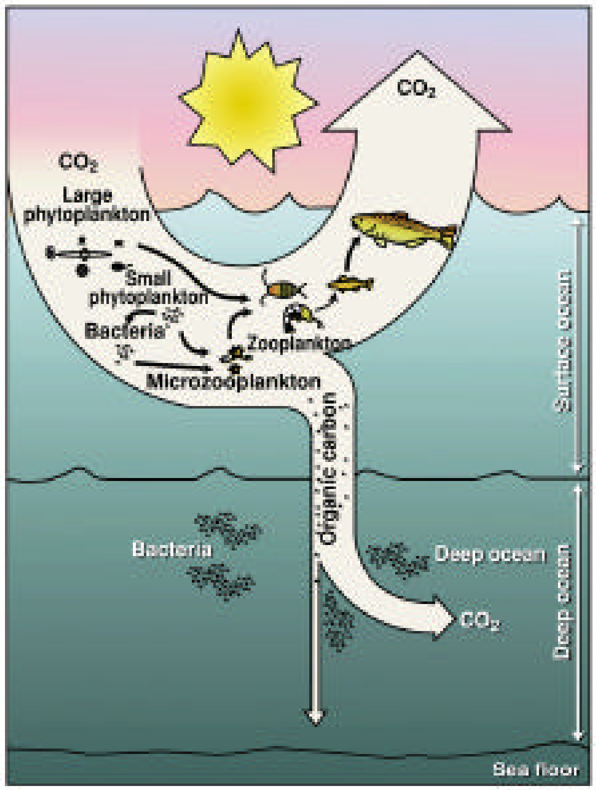
Source: DOE, 1999, p. 8-3

8.6.1 Sequestration in the Oceans

Ocean sequestration represents a large potential sink for CO_2. Although the ocean's biomass represents about 0.05% of the terrestrial ecosystem, it converts about as much inorganic carbon to organic matter (about 50 GtC/year) as do processes on land. The photosynthetic fixation of CO_2 by ocean organisms, followed by the sinking and slow remineralization (conversion to CO_2) of organic carbon, is a natural process for sequestering CO_2 in the deep sea. This process is often referred to as the "biological pump" (see Fig. 8.14). Eventually (over 1000 years), about 85% of today's anthropogenic emissions of CO_2 will be transferred to the ocean. Ocean sequestration strategies would attempt to speed up this ongoing process.

Iron fertilization is one promising method for accelerating the net oceanic uptake from the atmosphere. There is evidence that natural iron fertilization of the Southern Ocean was responsible for significant reductions in atmospheric concentrations of CO_2 following the onset of past ice ages. Iron fertilization is believed to enhance biological productivity of certain ocean regions, effectively transporting atmospheric CO_2 as biomass to lower regions of the ocean which have limited interaction with the atmosphere. Active experiments are already under way in iron fertilization and other tests of enhanced marine biological sequestration. Improvements in understanding marine systems would be needed before implementation of major marine sequestration campaigns, to enhance the effectiveness of applications and avoid undesirable consequences.

Fig. 8.14 A Schematic Diagram of the Biological Pump

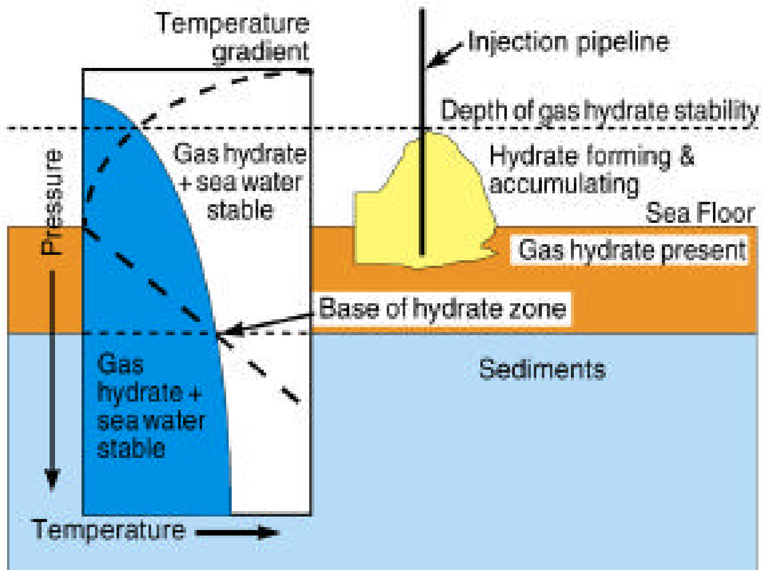


Source: DOE, 1999, p. 3.3

Another promising approach involves injecting relatively pure CO_2 streams that have been generated by a power plant or industrial facility directly into the ocean to be trapped in ice-like solids called gas hydrates. Gas hydrates are nonstoichiometric compounds in which the gas molecules are engaged within a host crystal lattice of water molecules. CO_2 could be pumped into regions such as deep oceans where hydrate is stable and sequestered as accumulated gas hydrate.

The drawing in Fig. 8.15 shows a conceptual cross-section of CO_2 introduced to a deep seafloor or within seafloor sediments. In arctic oceans, permafrost regions, and deep oceans, the pressure and temperature conditions favor gas hydrate stability. At deep ocean depths, CO_2 hydrates form below temperatures of 10°C. As a result of these same in situ processes, CH_4 hydrates form on the ocean floor and within ocean sediments. The sequestration process is the opposite of systems envisioned to extract CH_4 hydrates from the seafloor as an energy source. CO_2 could be piped into regions where hydrates are stable, to be sequestered as accumulated gas hydrates at the seafloor-ocean interface or within the accumulating sediments (the possible reservoir is basically unlimited because of the areal extent of ocean and permafrost regions where hydrates are stable). The advantages of the gas hydrate sequestration pathway are that hydrate formation results in a significant reduction in volume for equivalent mass and that the process may be less rate dependent than relying on CO_2 mixing with sea water.

Fig. 8.15 Conceptual Cross-Section of CO_2 Introduced to a Deep Seafloor



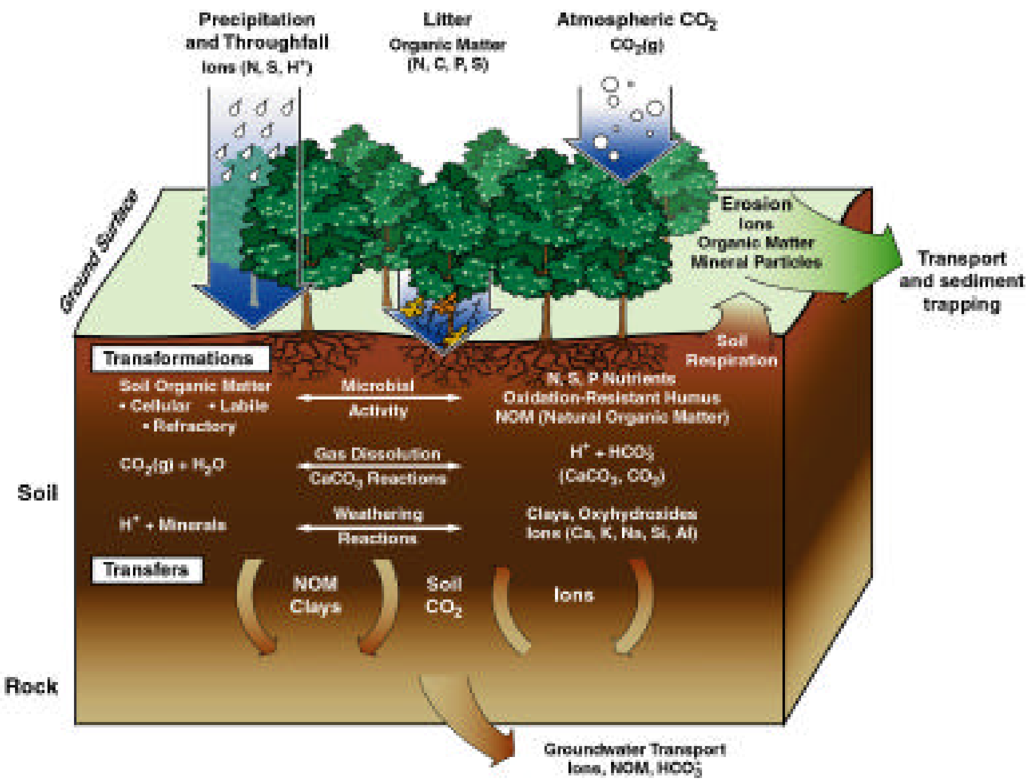
Source: DOE National Laboratory Directors, 1997, p. B-96

8.6.2 Sequestration in Terrestrial Ecosystems

The terrestrial biosphere is a large and accessible reservoir for sequestering CO_2 that is already present in the atmosphere. Terrestrial ecosystems, including forests, vegetation, soils, farm crops, pastures, tundra, and wetlands, act as huge natural biological scrubbers for CO_2. Computer models estimate that terrestrial ecosystems have a net carbon accumulation of about one-fourth (1.5 to 2 GtC) of the 7.4 GtC emitted annually into the atmosphere by fossil fuel combustion and land use changes. Their carbon sequestration potential could be significantly increased by careful manipulation to enhance the natural carbon cycle. Because natural carbon fluxes are huge, even small forced changes resulting from R&D advances would be very significant.

The potential for terrestrial ecosystems to remove and sequester more carbon from the atmosphere could be increased by reducing oxidation of soil carbon, enhancing soil texture to trap more carbon, and protecting wetlands. The dynamics of carbon transformations and transport in soil are complex and could result in either carbon sequestration or increased emissions of CO_2 (Fig. 8.16). Bicarbonate (HCO_3) ions dissolved in water could be sequestered if the dissolved carbonate enters a deep groundwater system that has a residence time of hundreds to thousands of years. Natural organic matter is another type of soil carbon that could be transported to deep groundwater systems. Natural organic matter could be mobilized during intense precipitation following prolonged dry periods. This carbon-rich material may be sequestered if it is transported to deeper groundwater systems or deposited deeper in soil. Thus, there may be opportunities to encourage geohydrologic systems to promote the deep transport of carbon into groundwater systems.

Fig. 8.16 The Dynamics of Carbon Transformations and Transport in Soil



Source: DOE, 1999, p. 4-9

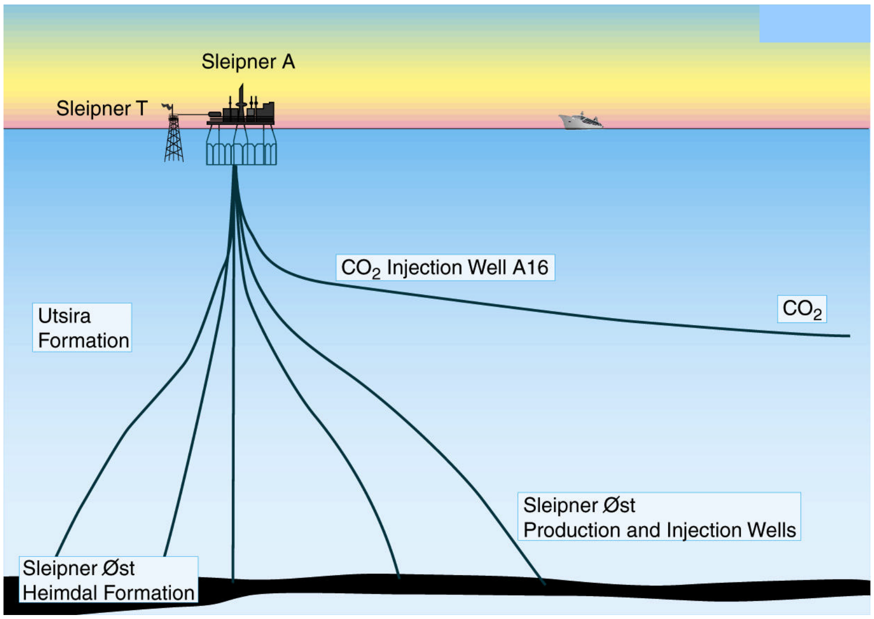
8.6.3 Sequestration in Geological Formations

CO_2 could be sequestered in geological formations by three principal mechanisms. First, CO_2 could be trapped as a gas or supercritical fluid under a low-permeability caprock, similar to the way that natural gas is trapped in gas reservoirs or stored in aquifers. This mechanism, commonly called hydrodynamic trapping will likely be, in the short term, the most important for sequestration. Finding better methods to increase the fraction of pore space occupied by trapped gas would enable maximum use of the sequestration capacity of a geologic formation. Second, CO_2 could dissolve into the fluid phase. This mechanism of dissolving the gas in a liquid such as petroleum is called solubility trapping. In oil reservoirs, dissolved CO_2 lowers the viscosity of the residual oil so it swells and flows more readily, providing the basis for one of the more common techniques for enhancing oil recovery.

Finally, CO_2 could react either directly or indirectly with the minerals and organic matter in the geologic formations to be come part of the solid mineral matrix. In most geologic formations, formation of calcium, magnesium, and iron carbonates could be the primary mineral-trapping processes. However, precipitation of these stable mineral phases is a relatively slow process with poorly understood kinetics. Developing methods for increasing the rate and capacity for mineral trapping could create stable repositories of carbon that are unlikely to return to the biosphere and could decrease unexpected leakage of CO_2 to the surface

About 70 oil fields worldwide use injected CO_2 for enhanced oil recovery. CO_2 sequestration is already being practiced in a sub-seabed reservoir in the North Sea of Norway (Fig. 8.17). The United States appears to have sufficient capacity, diversity, and broad geographical distribution of potential reservoirs to enable widespread usage of geologic sequestration.

Fig. 8.17 A Norwegian CO_2 Injection System



The primary uncertainty is the effectiveness of storing CO_2 in geological formations—how easily CO_2 can be injected and how long it will remain. It is not yet possible to predict with confidence storage volumes and integrity over long time periods. Many important issues would need to be addressed to reduce costs, ensure safety, and gain public acceptance.

8.6.4 Advanced Biological Processes

Advanced biological processes could be developed and implemented to limit emissions and capture and sequester carbon. Bacteria and other organisms could be used to remove carbon from fuels and to recycle carbon from man-made waste streams. Crop wastes and dedicated crops could be used as feedstocks for biological and chemical conversion processes to manufacture fuels and chemicals. In addition, advanced crop species and cultivation practices could be designed to increase the uptake of atmospheric CO_2 by terrestrial and aquatic biomass while at the same time decreasing CO_2 emissions to the atmosphere from soils and terrestrial and aquatic biomass.

The 21st Century has been referred to as the "Century for Biology." Indeed, many new molecular tools have been developed that could aid in new discoveries and assist in providing solutions to key problems facing humankind and the planet. The difference that advanced biological techniques could make will be evident when they are integrated with land, subsurface, and ocean management practices.

8.6.5 Advanced Chemical Approaches

Improved methods of separation, transport, and storage of CO_2 could benefit from research on and development of advanced chemical techniques to address sequestration via chemical transformations. Any viable sequestration technique must store vast amounts of carbon-rich materials. Thus, environmental chemistry could be valuable to determine whether these materials would be stable when sequestered. Many issues pertaining to aqueous carbonate/bicarbonate chemistry are relevant to sequestration of carbon in oceans, geological formations, and groundwater. Carbonate chemistry in very basic solutions could lead to a method for extracting CO_2 from air. Clathrates, compounds that can enclose molecules such as CO_2 within their crystal structure, could be used to separate CO_2 from high-pressure systems. Learning clathrate properties may be important to understanding chemical approaches to ocean storage of carbon. Subsurface arctic and marine hydrate formations could also be viable as geologic sequestration options.

The proper focus of R&D into advanced chemical sciences and technologies is on transforming gaseous CO_2 or its constituent carbon into materials that either have commercial value or are benign, inert, and contained in the earth or water of our planet.

In the long-term, carbon sequestration could play a significant role. In fact, low-cost carbon sequestration techniques could enable the nation’s continued reliance on its vast fossil fuels resources for large-scale energy production. It could allow greater flexibility in the future primary energy supply. In addition, it could offer other benefits such as the manufacture of commercial products (e.g., construction materials and plastics); improved agricultural practices that could reduce soil erosion, conserve water and increase the sustainability of food production; the restoration of wetlands, which would help preserve wildlife and protect estuaries; increased biodiversity; enhanced recovery of oil and methane (from coal beds); and the development of exportable technologies to help the U.S. economy.

8.7 CROSSCUTTING TECHNOLOGIES

A number of technologies crosscut a wide range of applications that could enable significant energy efficiency gains, facilitate increased use of clean energy, and reduce the costs of sequestering carbon. Advancing these crosscutting technologies integrates the pull of technology with the push of basic science.

This subsection describes four crosscutting technology areas: hydrogen and fuel cells; electrical transmission, distribution, and components; sensors and controls; and energy storage. Further details about the RD&D required to advance these technologies are presented in Appendix B of the DOE National Laboratory Directors (1997) report.

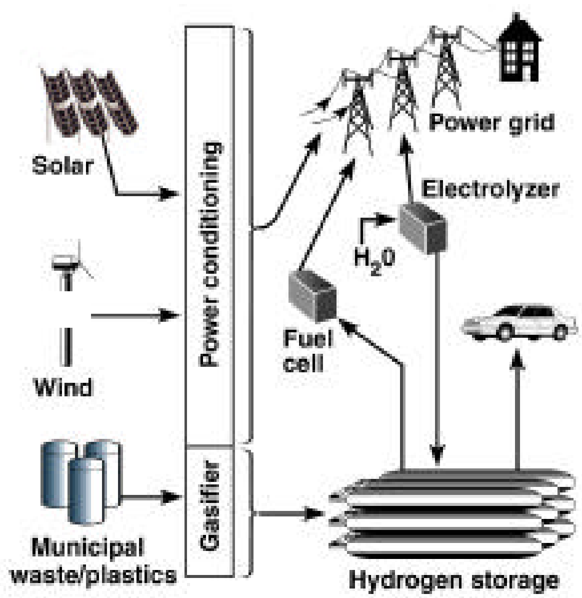
8.7.1 Hydrogen and Fuel Cells

Hydrogen is a carbon-free energy carrier that could be used to energize every aspect of society. For example, it could fuel transportation vehicles (air and ground), provide heat for industrial processes, supply domestic heating needs through cogeneration or heat recovery systems, and fuel power plants for centralized or distributed electrical generation. Integrated systems that combine electricity generation with a hydrogen transportation fuel system could offer significant economies of scale and could accelerate the penetration of renewables into the marketplace (Fig. 8.18).

Hydrogen is an energy carrier that must be produced efficiently from a primary energy source. Depending on the source, its production may or may not involve CO_2 emissions. When hydrogen is produced from carbon-containing primary energy sources, CO_2 appears as a concentrated byproduct; subsequent sequestration could result in low emissions of CO_2 depending on the amount of fossil energy used in the hydrogen production process. Hydrogen from biomass or solid wastes could result in very low CO_2 emissions, depending on the amount of fossil fuel used for fertilization, cultivation, and transportation of the bioenergy feedstock. Zero-carbon dioxide hydrogen production concepts include:

- electricity converted to hydrogen by electrolysis of water, and
- photoelectrochemical and photosynthesis-based processes for producing hydrogen from water.

Fig. 8.18 An Integrated Hydrogen Fuel Cell System



Source: DOE National Laboratory Directors, 1997, p.3-10.

Before hydrogen can be a major energy carrier, infrastructure must be greatly improved (e.g., storage technologies and distribution systems). Advanced storage concepts include metal hydrides, carbon adsorption, and carbon nano-tube encapsulation. Many of the more promising concepts are still in the basic research stage. Distribution systems would also have to be deployed that are capable of containing and pumping the low molecular weight fuel, and resisting embrittlement.

Hydrogen could be used in modified conventional combustion energy conversion devices (e.g., engines) to ease the transition to a completely new energy infrastructure where hydrogen would be used in fuel cells for energy conversion. Fuel cells promise potentially higher system efficiency and solid-state operation with water as the only effluent.

Fuel cells convert chemical energy directly into electrical energy; no combustion is involved. Operating on hydrogen, a fuel cell does not emit CO_2 and is projected to be up to two times as efficient as other advanced power generation technologies. A highly efficient end-use/conversion device such as a fuel cell would be necessary to offset the energy penalty associated with producing hydrogen and to achieve the full benefits of a transition to a hydrogen economy.

A fuel cell power plant typically consists of three main parts:

- a fuel processor that converts a fuel (e.g., natural gas, diesel fuel, ethanol, methanol, gasoline) to a hydrogen-rich gas,
- the fuel cell stack system that converts hydrogen into direct-current (dc) electricity, and
- a power conditioner that converts the dc electricity to regulated alternating-current (ac) electricity.

Fuel cells span all important energy use sectors. They are commonly classified according to the type of electrolyte employed. Molten carbonate and phosphoric acid fuel cells target power generation, both large-scale and distributed power production. Solid-oxide fuel cells are mostly considered for stationary application. Proton exchange membrane fuel cells target transportation as well as distributed power applications. Along with electricity, fuel cells produce heat, which could be used directly or, if the temperature is high enough, as input to a bottoming cycle to produce additional electricity. In the long run, hydrogen could become the world's principal energy carrier. It provides energy security because it could be produced efficiently from numerous domestic sources. It can be stored, thereby eliminating the drawbacks of intermittent renewable electric technologies. In addition, it could be transported by pipeline from remote renewable resource locations to load centers.

A hydrogen energy system would allow a gradual transition from fossil fuels to non-carbon primary energy sources while reducing CO_2 and other emissions. At full market penetration, all conventional use of fossil fuels would be replaced by hydrogen derived from renewable or carbon-sequestered fossil-fuel sources. Before hydrogen could achieve this premiere status in the energy economy, however, significant advances would be required in hydrogen production, storage and distribution technologies, and in the performance and cost of fuel cells and carbon sequestration.

8.7.2 Transmission and Distribution Technologies

Many proposed clean energy technologies involve alternative ways of producing electricity. In most cases, the U.S. electric transmission and distribution system is the means by which these alternative approaches could be made available to energy users. Almost 40% of the capital investment currently required to produce and deliver electricity goes to construct transmission and distribution facilities. The availability of reasonably priced transmission capacity will be crucial to the commercial success of alternative generation strategies. This is particularly a concern for large-scale development of remote renewable resources such as geothermal and wind power, which often require significant investments in new transmission capacity because of the distances between the best resource areas and load centers. At the same time, public opposition to the construction of conventional transmission lines for environmental reasons has focused attention on opportunities for increasing the capacity of existing corridors, as well as on development of transmission technologies that are compatible with public concerns and therefore present a minimum of permitting risk. In addition, the importance of other collateral benefits of these technologies cannot be overlooked, especially their contribution to improving power quality and reliability.

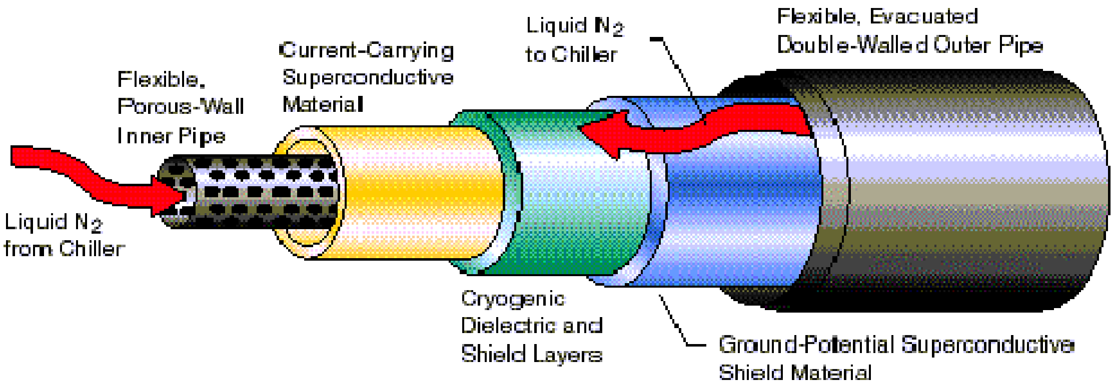
R&D would be needed on automated system control technologies that better use the capacity of existing systems, as well as advanced composite-reinforced high-strength overhead line conductors to increase the capacity of individual lines. Developments in power electronics – including wide-bandgap semiconductors for high-power switching devices and advanced converter designs – would be needed to improve power management on existing systems and to enable high-voltage DC transmission for long-distance power transfers.

Electric power has two characteristics that make it a unique commodity. First, because there are essentially no commercially viable, large-scale and inexpensive energy storage options (although this gap may be filled in the future – see Section 8.7.4), aggregate production and consumption must be balanced essentially instantaneously. Second, it is inordinately expensive to control the power flow over individual lines, power flows are dictated by generator and load locations and the impedances of the interconnecting lines. Power electronics hold the promise of dramatically changing the nature of the electric power industry if they can lower the cost of line flow control. This would greatly increase the transmission system utilization and reduce the need for additional transmission lines.

Seven and one-half percent of electricity generated in the United States each year is currently lost due to the resistance of copper and aluminum wire. By the middle of the 21st century, the electricity superhighway could be dominated by high-temperature superconducting (HTS) wires in cables (Fig.

8.19), transformers, and current controllers. Superconductors, which have nearly zero resistance, could make available most of the energy that is currently lost in distribution, without requiring any additional fossil fuel use or generating capacity. In addition to reducing electricity losses, HTS materials could strengthen the reliability of the U.S. electricity infrastructure, eliminate hazardous materials from electrical systems, and create thousands of new high-technology domestic jobs. Research is needed to scale up second-generation HTS "coated conductors" to lengths for use in power equipment.

Fig. 8.19 Cross-Sectional View of Cold Dielectric Design of High-Temperature Superconducting Cable



8.7.3 Sensors and Controls

Sensors and controls could play a significant role in enabling many technological pathways to a clean energy future. By maximizing system efficiencies at minimal cost, sensors and controls have a broad range of potential applications.

Some of the key attributes of future sensor technologies will likely be the integration of transduction, signal conversion, information abstraction and telecommunication on a single chip and an ability to adapt to changing system requirements. The combination of scalability and decreasing cost with increasing functionality that has been evidenced in semiconductor devices will likely prevail in sensor technologies as well. Revolutionary advances could take place in materials for sensors and integrated circuits that would allow devices to become more robust in harsh operating conditions and facilitate a paradigm shift in how sensors are employed (measuring from the inside and communicating out, rather than attached to the outside looking in). The integration of biological molecules and systems with emerging solid state device technologies foretells of the advent of molecular electronics and nano-technology systems with practical use. All types of sensors and sensor/actuator systems could have the potential for integration in systems where the sensor itself becomes a node on a potentially vast distributed network. In such systems, the sensors would be essentially free, and the information would become the commodity for sale.

Many of these technologies are emerging now and engender the excitement that micro-electro-mechanical systems (MEMs) produced some 20 years ago. As MEMs evolve they could play an important role as the transducer or actuator in many integrated systems. In addition to electro-mechanical integration on a miniature scale, chemo-electro-mechanical and bio-electro-mechanical devices could emerge and play a key role in many process and environmental measurement applications.

With the advent of carbon-fullerene micro-spheres and now carbon nano-tubes, we see the never-ending push toward assembling system atom-by-atom or certainly molecule-by-molecule. Tailored materials, at the atomic scale, are a critical element of the ultimate sensor system construct wherein machines become self-aware through the use of massively-distributed sensor networks that possess sufficient embedded intelligence to perform cognitive tasks in relation to mission requirements, their operating environment, and their own ability to perform within the mission context.

Numerous specific energy applications for advanced sensors and controls are already becoming a reality, while many others are envisioned for the future. For example, chemical sensors capable of operation in boreholes could improve fossil fuel recovery. Both refining processes and fossil fuel reforming for CO_2 sequestration at the wellhead require substantial chemical processing that could be enhanced through real-time process sensors and controls. Sensors and controls that more accurately measure operational parameters could also be used to increase the output of nuclear power plants. Improved sensors and controls also allow operation closer to theoretical materials and process limits, which improves efficiency in processes such as fossil-fired power generation.

In the area of energy efficiency, novel sensors would be needed in the transportation sector to enable the use of more efficient engine technologies. Oxygen, NO_x, and knock sensors and engine control technologies would be necessary to optimize the various lean-burn internal combustion engines, compression-ignited/direct-injection engines, and diesel engines being developed. Pattern recognition, artificial intelligence, fuzzy logic, and other enabling technologies for real time data analysis and "sensor fusion" would also be needed. Almost all industrial processes depend on sensors and controls to ensure the quality of goods produced, and advanced sensors could help to reduce wasted energy, CO_2 emissions, and other pollutants. Across the industrial arena, sensors would be needed that could be used in harsh environments and that would measure such on-line process parameters as viscosity, moisture, chemical composition, density, flow, temperature, and pressure. The next half century could witness the close integration of sensors and microtechnologies that could use "smart controllers" to provide real-time on-line process control to improve productivity and decrease energy requirements.

In carbon sequestration, innovative sensors for analyzing photochemical processes and carbon fixation would be needed. The same family of sensors could be used to increase the production of energy crops.

Often a single fundamental sensor technology would meet the needs of different applications, so sensors are a true crosscutting technology. An excellent example of this is the solid-state oxygen sensor developed for the space program in the 1960s. This sensor is now universally used in gasoline engine control and is common in industrial combustion control, touching virtually every major energy-consuming industry. A large variety of novel sensor technologies that are robust, fast, inexpensive, wireless, miniature, and capable of supporting real-time control could be available and widely used by 2050. It is possible that the next half-century would produce a new generation of techniques for fabricating electronic devices that would allow unprecedented miniaturization of sensors and associated electronic controls.

8.7.4 Energy Storage

Stationary energy storage is now primarily in the form of bulk storage of fossil fuels (piles of coal, oil in tanks, gas in pipelines) and water in reservoirs. Reversible energy storage technologies in use today include pumped hydropower, compressed air, and chemical batteries for small uninterruptible power. Advanced storage technologies under active development include processes that are mechanical (flywheels, pneumatic), electrochemical (advanced batteries, reversible fuel cells, hydrogen), and purely electrical (ultracapacitors, superconducting magnetic storage). The major hurdle for all storage technologies is cost reduction.

Advanced energy storage concepts could improve system efficiencies and reduce carbon emissions in most sectors of the economy.

- **Power:** The efficiency of a typical steam plant falls from about 38% at peak load to 28–31% range at night. In the future, utilities could store electrical energy at off-peak times, allowing power plants to operate near peak efficiency. The stored energy would be used during peak demand times. CO_2 emissions would be reduced if the efficiency of the energy storage were greater than 85%. Battery use for peaking could also lessen the need for lower-efficiency peaking units by charging with higher efficiency units during low demand, but the net emissions depend on the relative cleanliness of the two. Battery-powered electric vehicles could serve as a distributed off-peak energy storage system, but higher turn-around efficiency than the 70% of lead-acid batteries is needed. In the long term, as demand grows, renewable sources could be added to the grid that could use storage to achieve dispatchable power for peaking, to improve power quality, and to more fully utilize the connecting transmission system.
- **Vehicles:** Energy storage in automotive electric and hybrid drive trains allows regenerative braking, which can reduce fuel consumption by 25% on the urban driving cycle. Additional optimization of engine size in hybrids to allow better average-power matching could improve total powertrain efficiency by a factor of 2 over existing automobiles. Energy storage and power density for automotive applications must be lightweight and have high cycle life (100,000s of cycles). Bus and delivery heavy-duty vehicles could also benefit from hybrid powertrains, although the improvement is not likely to be as great as for automobiles.
- **Home cogeneration:** Small amounts of energy storage could be a pathway to commercially viable home cogeneration using solid oxide fuel cells or optimized engines coupled to small generators that are fueled with natural gas. Storage of a few kilowatt-hours with power output of 5–10 kW would reduce the start-stop cycles on the fuel-to-electricity converter, lower the size of generator needed, and improve the efficiency of the overall system. Waste heat from the converter would be used for space heating and domestic hot water. Such systems could use 70–90% of the fuel energy, depending on seasonal heating requirements. If the fuel converter had greater efficiency than central power plants along with their transmission losses, these systems could be connected to the grid to carry out distributed power peaking.

In transportation, hybrid powertrains that use batteries, flywheels, or ultracapacitors in conjunction with engines allow the reduction of engine size. A hybrid powertrain could increase overall efficiency by up to 100% without a loss in vehicle performance (acceleration, range, and passenger capacity). Advanced energy storage could enable electric utilities to shift generation to off-peak periods and to better use intermittent renewable energy sources, such as solar PVs and wind, that produce no direct CO_2.

8.8 CONCLUSIONS

A consideration of the longer term makes clear the tremendous variety of possibilities that exist for energy futures. The discussion of energy technologies under development in this chapter gives a sense of the many different technological opportunities that could alter these futures. It is of course not possible to know which of the infinite number of possible energy futures will happen.

In spite of the many uncertainties about the future and the richness of choice that will exist over time, there are several observations that appear highly likely. The first, and probably most important, is the increasingly dominant role that developing nations will play in world energy markets. In all of the IPCC "marker" scenarios – and indeed in all the major energy scenarios developed by international energy analysts (Nakicenovic, et al, 2000) – a very high percentage of energy demand growth takes place in the developing world. As we noted earlier, three of the four IPCC "marker" scenarios showed that 90% or more of the increase in energy demand will occur in developing countries between the present and 2050, and the fourth showed more than 75%.

This does not mean that the industrialized world need not be concerned about energy demand, since such a large portion of the growth will be in developing countries. Quite the contrary: most opportunities for developing and applying clean energy technologies will likely occur first in industrialized countries.

A second important observation from this chapter is the tremendous richness of opportunities to improve the global energy future over the longer term. There are numerous technologies that could make a huge difference in the environmental impacts of energy production, transmission, and distribution; avoiding future stresses on the energy system by much higher efficiency of energy end-use; and in reducing direct economic as well as environmental and social costs of energy use.

Thus, there appear to be two important lessons from this chapter that provide a broader perspective to the CEF results for the United States:

- R&D on advanced energy systems has the potential to lead to important new technologies; such technologies can provide enormous benefits to society, especially in the longer term, and
- This R&D should be done with an eye to applications in the developing world, since a very large portion of energy demand growth is highly likely to occur in these developing regions.

Given the uncertainties in global economic trends, demographics and lifestyles, air quality, and climates, an expanded R&D effort in most energy technology arenas would appear to be warranted. There is a broad range of longer-term technology options which, with successful research, could provide additional solutions to the energy-related problems facing the nation and the world.

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