# APPENDIX B

## *FACTUAL DOCUMENT*

# INTRODUCTION

This document consists of a series of white papers providing data and background on key energy sources and applications that sustain the U.S. and international economies. These papers have been prepared to support the Office of Basic Energy Sciences (BES) and their Advisory Committee (BESAC) in their evaluation of energy research needs and options for the future. Based on the panel structure established for this evaluation, these white papers address the following energy options:

- fossil energy (including coal, gas, and oil)
- nuclear fission energy
- renewable and solar energy
- nuclear fusion energy
- distributed power generation, fuel cells, and hydrogen
- transportation energy consumption
- residential, commercial, and industrial consumption

Standalone papers have been prepared for each of these panel topic areas. As a result, some repetition exists among the topics. For example, fuel cells are discussed briefly in several papers, but covered in detail under distributed generation.

In addition to background information, the papers also include some discussion of relevant research activities and opportunities. It is important to mention that much energy technology research is more applied than typical for BES. Such research is likely funded by private industry or the DOE applied program offices (e.g., Energy Efficiency or Nuclear Energy). The discussion of applied research can clarify the range of issues that must be dealt with before a given technology can be successfully implemented, and may be helpful in defining the research components of interest to BES. Each of the white papers includes a list of references or resource materials. In addition, most of the data was obtained from the *Annual Energy Review, Annual Energy Outlook,* and the *International Energy Outlook* .

To provide a common base of comparison, the energy data was converted from traditional units such as Quad ($10^{15}$ Btu) and kWh to SI units. For example, the closest equivalent to the Quad is an Exa-Joule (EJ) ($10^{18}$ J), where 1 Quad = 1.055 EJ. A list of conversion factors for common energy units is contained in Table 1.1.

**Table 1.1. Energy conversion factors for common units**

| Conversion factors | Metric prefixes |
|---|---|
| 1 Watt (W) = 1 Joule/second (J/s) | milli = m = $10^{-3}$ |
| 1 Quad = 1 x $10^{15}$ Btu = 1.055 x $10^{18}$ J = 1.055 EJ | pico = p = $10^{-12}$ |
| 1 barrel oil = 5.63 x $10^{9}$ Joule = 5.63 GJ | Kilo = k = $10^{3}$ |
| 1 cubic ft gas = 1.08 MJ | Mega = M = $10^{6}$ |
| 1 ton coal = 22.2 GJ | Giga = G = $10^{9}$ |
| 1 kWh = 3.6 MJ | Tera = T = $10^{12}$ |
| $10^{9}$ kWh = 3.6 x $10^{15}$ J = 3.6 x $10^{-3}$ EJ | Peta = P = $10^{15}$ |
|  | Exa = E = $10^{18}$ |

Although this document focuses on U.S. energy research needs, the issues of U.S. energy production and consumption can not be divorced from international energy issues. Therefore, this introduction will be presented in three parts. First, some aspects of the current global energy picture will be summarized. This will be followed by a section that presents recent U.S. energy supply and consumption data. A comparison of U.S. and international energy consumption data will comprise the final segment.

### Global Energy Issues

To properly assess future U.S. energy needs, it is necessary to compare current energy consumption with the anticipated future global energy picture. The mean global energy consumption rate was 13 TW in the year 2000, with the U.S. consuming about a quarter of that amount. Of this, oil accounted for 4.5 TW, coal for 3 TW, natural gas for 2.7 TW, hydro for 0.3 TW, biomass for 1.2 TW, and other sources 1.8 TW. Note that a mean energy consumption rate of 1 TW= 31.5 EJ/yr.

The world population is expected to grow to 10-11 billion people by the year 2050, and this growth will be concentrated in the developing counties. This population growth, together with the standard of living goals for these developing countries, will have a substantial impact on energy consumption patterns if reduced emission of greenhouse gases becomes an important goal. Meeting these emerging energy needs without increasing greenhouse gas levels will limit the use of fossil fuels everywhere in the world, including the U.S., and require huge amounts of carbon-free energy.

The required quantities of energy are quite staggering, and have been summarized in recent publications [Hoffert, 1998; Hoffert, et al., 2002]. Energy projections are strongly dependent on the assumptions made in extrapolating current trends. The essence of the analysis by Hoffert and coworkers is based on three reasonable assumptions:

1. an expected population of 10-11 billion by the year 2050,
2. an increase in the average world Gross Domestic Product (GDP) of 1.6%/yr (historical average),
3. energy growth is counterbalanced by a decrease of 1%/yr in the energy consumption per unit of GDP because of expected increases in the efficiency of energy utilization.

These assumptions result in an expected energy consumption in the year 2050 of 28 TW, which is more than double the present world energy consumption rate of 13 TW. Although fossil fuel resources and proven reserves are huge (40,000 EJ for oil plus gas and 180,000 EJ for coal, enabling their possible use for about 50 years for oil and gas and 275 years for coal), their use may be severely restricted by the problems of $CO_2$ emissions.

The present $CO_2$ concentration in the atmosphere is 325 ppm, compared with a pre-industrial value of ~275 ppm. If the $CO_2$ concentration in the atmosphere is to be restricted to 550 ppm in the year 2050 (which is twice the pre-industrial value), about 20 TW of carbon-free power will be required. This is appreciably more than the total world energy consumption today. Furthermore, even if no restrictions on $CO_2$ emissions were implemented, just to maintain the present rate of decrease in carbon intensity of energy utilization (at a rate of –0.56 kg C/yr/watt) will require 10 TW of carbon-free energy by year 2050. This is also a huge and daunting requirement. A similar case for the need for daunting amounts of carbon-free power can be advanced based on sustainability arguments even in the absence of greenhouse gas effects.

Global electricity production amounted to about 1.3 TW in 1998. Of this, nuclear power provided 0.83 TW. Hydroelectric power produced 0.29 TW as the largest renewable power source. The 1.2 TW of biomass power produced in 1998 was unsustainably burned biomass, as opposed to renewably-farmed biomass. Other renewable energy, including renewable biomass, provided only 0.29 TW of power. Sustainable biomass power production, which can be broken down into electrical power, heat, and ethanol, contributed a total of $10^{-1}$ TW out of the 12-13 TW of total primary power produced globally in 1998. Wind produced $2 \times 10^{-3}$ TW of power. Solar electric power production is growing rapidly, but from a very small base, providing about one-millionth of the total global primary power. Solar thermal and other renewable resources are also currently small fractions of the overall primary energy supply.

The available global renewable resources are estimated to be: (1) hydro: 4.6 TW total, 0.9 TW practical, and 0.7 TW already installed; (2) wind: 50 TW total on land, 2 TW practical on land (higher if oceans are utilized); (3) biomass: 5-10 TW total (not considering land required for food production and utilizing 100% of the cultivatable cropland for energy production); (4) solar: $1.2 \times 10^5$ TW total; practical: 600 TW (60 TW at 10% conversion efficiency) (to generate 12 TW of solar power at 10% efficiency would require 0.1% of the worlds land mass). Nuclear energy from fission can provide substantial amounts of carbon-free electricity and process heat from known uranium resources for about 50 to 100 years at current levels of consumption. The implementation of known breeder reactor technology would significantly extend the time over which fission could contribute.

These numbers suggest that among the energy sources traditionally considered to be "renewable," only solar could provide the required carbon-free energy. This could be implemented as biomass or as photovoltaic or advanced solar conversion technology. However, breakthroughs and disruptive technology are required to achieve such a level of implementation. Similarly, nuclear fusion remains a promising long-term energy source, with substantial research and development required before it can contribute to global energy production.

### U.S. energy supplies and consumption

Figures 1.1 to 1.5 represent energy sources and energy consumption in the U.S. for the year 2000. The data in Figures 1.1 to 1.4 emphasize both relative and absolute values in each case.

Figure 1.1 shows sources of energy used. Values are for domestically produced supplies, except for net imports. Net imports include oil (25.8 EJ), gas (4.1 EJ), and other (0.8 EJ) imports, minus oil (2.3 EJ), gas (0.3 EJ) and coal (1.6 EJ) exports.

U.S. energy consumption values shown in Figure 1.2 include both end-use consumption by the major sectors of the economy plus the energy lost as heat through generating electricity at power plants. Electricity generation on average was 32% efficient, with 68% of energy lost in conversion. Each sector includes both electricity end-use and primary energy use (i.e., oil or gas).

The primary energy sources used in generating electricity are compared in Figure 1.3. This includes co-generated electricity sold on the grid, but does not include electricity generated by industrial firms and used on-site. Coal represents the major contributing source for generation.

Both electricity and non-electricity generating sources of renewable energy are shown in Figure 1.4. Starting clockwise in Figure 1.4, Hydro through Wind represents the renewable energy used for electrical generation available on the power grid. Hydro-Industrial through all Biomass uses represents energy used directly in the sector. Biomass-Residential represents wood burning sources. Ethanol production is used in gasoline blending.

As shown in Figure 1.5, use of electricity is almost evenly split among residential, commercial, and industrial sectors. Electricity represents only 13% (3.9/29) of overall energy use for the industrial sector versus 36% for residential and 46% for commercial use. Electricity use in transportation is negligible.

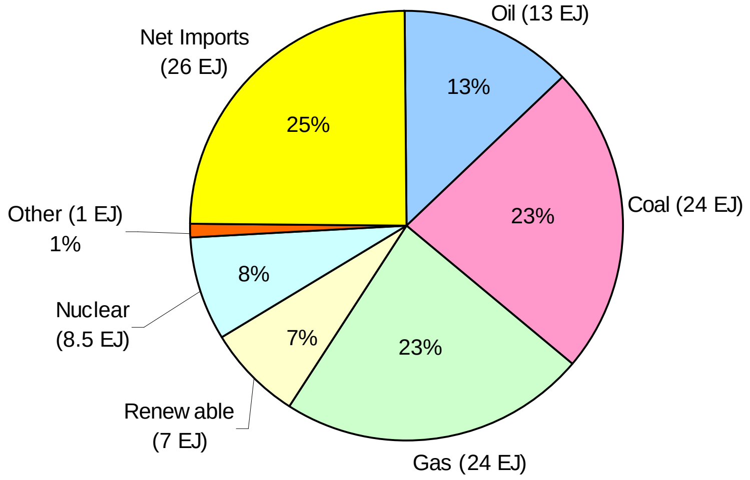

**Figure 1.1. Year 2000 U.S. Energy Supply (EJ)**
*Source: EIA 2002*

The categories of proven fossil energy reserves for both the U.S. and international communities are shown in Figure 1.6. The data does not include nonproven reserves such as oil shale or tar sands. Coal dominates the fossil reserves. The U.S. has a significant fraction of the total coal supplies but much smaller proportions of the oil and gas supplies.

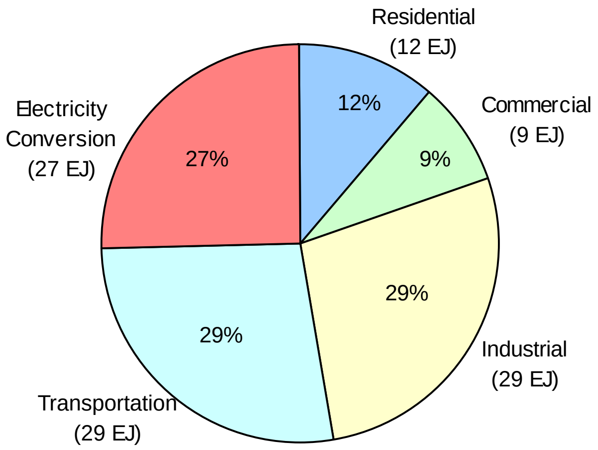

**Figure 1.2. Year 2000 U.S. Energy Consumption (EJ)**
*Source: EIA 2002*

## Comparison of U.S. energy and international energy consumption

Figure 1.7 compares U.S. and international consumption of primary energy sources in the year 1999. Energy consumption data for individual countries, along with their GDP expressed in 1997 U.S. dollars, is listed in Table 1.2. The U.S. is characterized by both high-energy consumption and high GDP. The third column in the table lists the energy consumption per unit GDP. Based on this parameter, the U.S. appears less efficient than many industrialized nations, but much more efficient than most developing nations.

## References

Hoffert, M. I. 1998. *Nature*. **395**. p. 881.

Hoffert, M. I., et al. 2002. *Science*. **298**. p. 981.

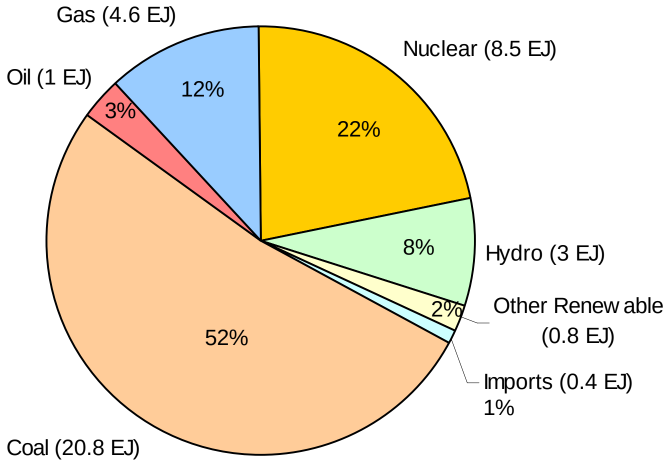

**Figure 1.3. Year 2000 U.S. Electricity Generation (EJ)**
*Source: EIA 2002*

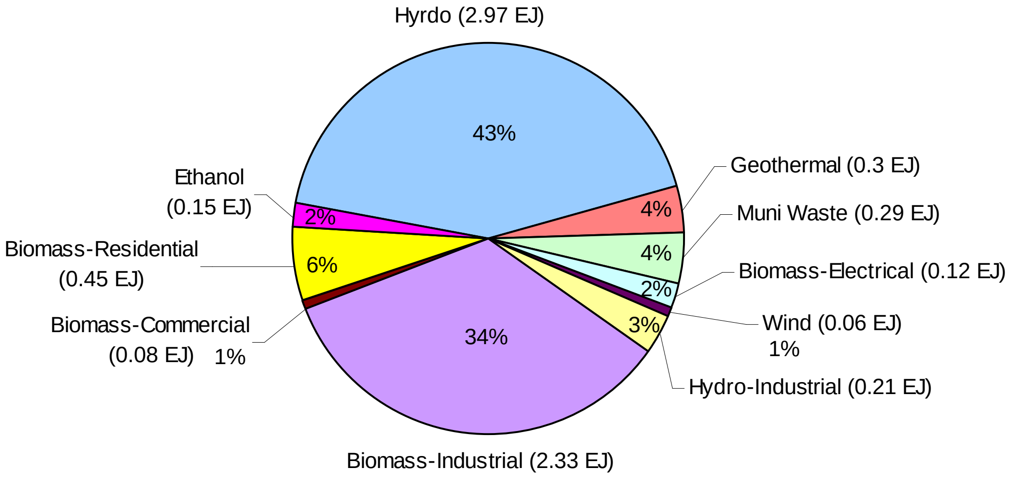

**Figure 1.4. Relative Contribution of Various Renewable Energy Sources in Year 2000 (EJ)**
*Source: EIA 2002*

## Other Resources

International Energy Agency. 2000. IEA-2000. *International Energy Annual 2000.* Paris, France.

U. S. Department of Energy. Energy Information Administration. 2001. *Annual Energy Review 2000.* Washington, DC. August. (http://www.eia.doe.gov/emeu/aer/contents.html)

U. S. Department of Energy. Energy Information Administration. 2002. EIA 2001. *Annual Energy Outlook 2002 with Projections to 2020*. DOE/EIA-0383(2002). Washington, DC. December. (http://www.eia.doe.gov/oiaf/aeo/index.html)

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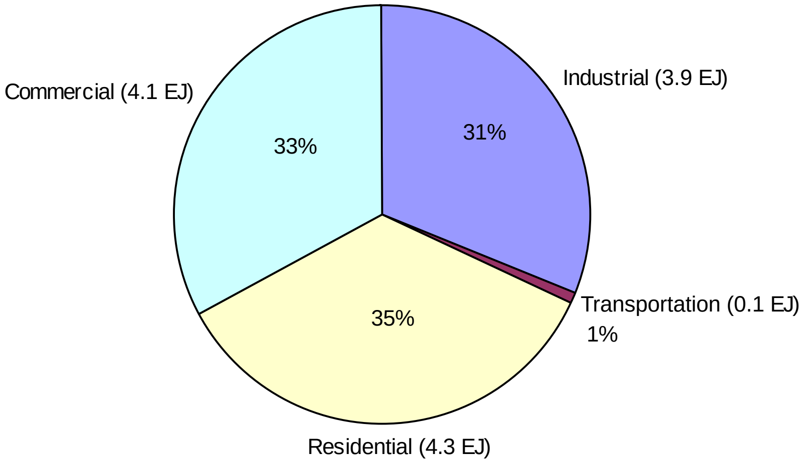

**Figure 1.5. Year 2000 U.S. Electricity Consumption (EJ)**
*Source: EIA 2002*

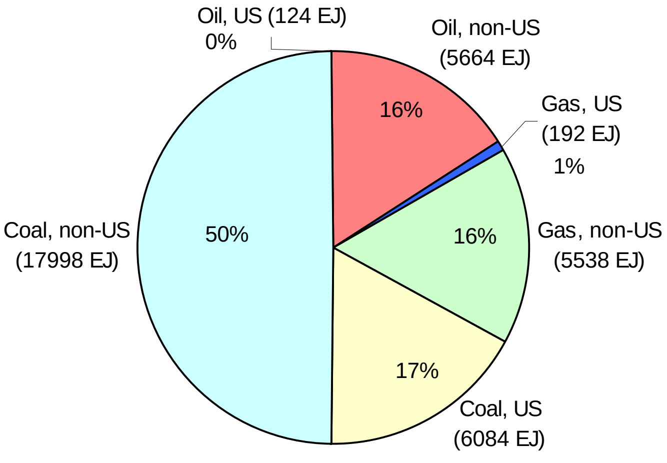

**Figure 1.6. World Fossil Energy Proven Reserves (EJ)**
*Source: EIA 2002*

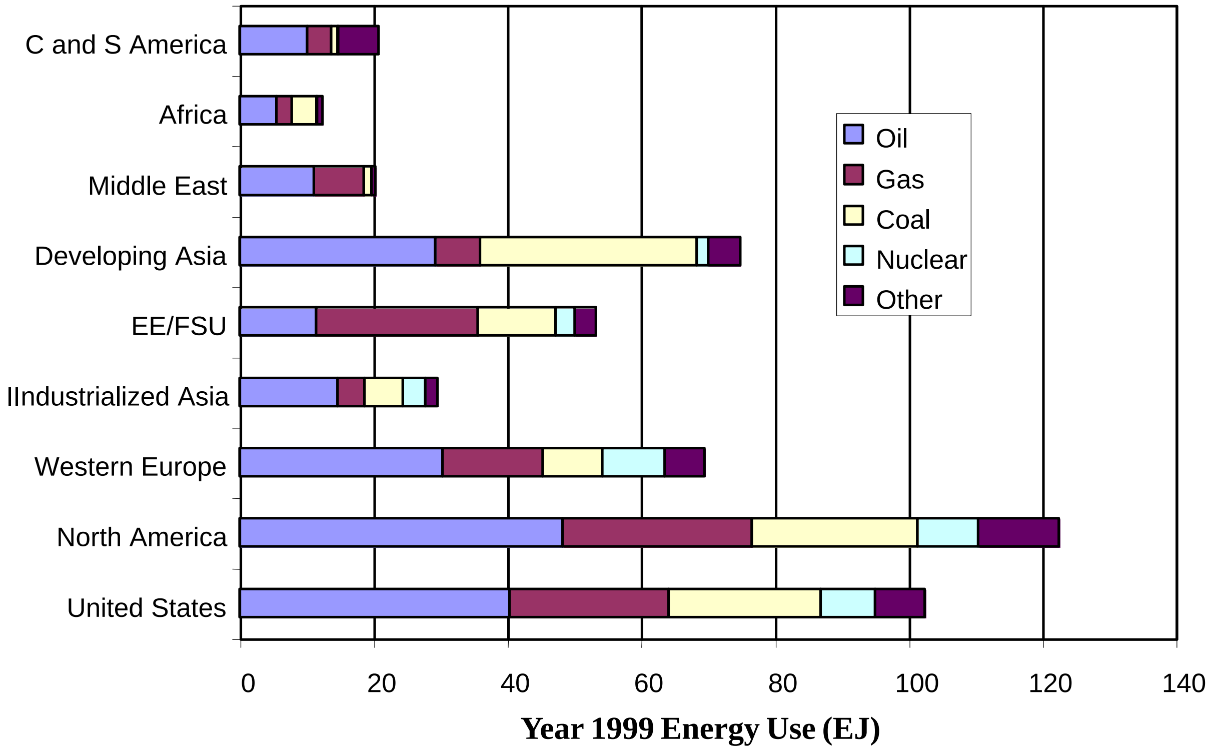

**Figure 1.7. Year 1999 International Energy Use by Region and Fuel Source**
*Source: IEO-2002*

## Table 1.2. Year 1999 World Energy Use and GDP by Country and Region

| | GDP (Billion 1997 $) | Energy (EJ) | MJ per $ GDP |
|---|---|---|---|
| **North America** | 10,165 | 122 | 12.0 |
| United States | 9,029 | 102 | 11.3 |
| Canada | 699 | 13 | 18.9 |
| Mexico | 437 | 6 | 14.7 |
| **Western Europe** | 8,944 | 70 | 7.8 |
| United Kingdom | 1,384 | 10 | 7.5 |
| France | 1,499 | 11 | 7.2 |
| Germany | 2,187 | 15 | 6.8 |
| Italy | 1,207 | 8 | 7.0 |
| Netherlands | 407 | 4 | 9.9 |
| Other Western Europe | 2,260 | 21 | 9.3 |
| **Industrialized Asia** | 4,821 | 29 | 6.1 |
| Japan | 4,304 | 23 | 5.3 |
| Australasia | 516 | 7 | 12.7 |
| **Total Industrialized** | 23,930 | 221 | 9.2 |
| Former Soviet Union | 569 | 41 | 72.7 |
| Eastern Europe | 363 | 12 | 32.6 |
| **Total EE/FSU** | 932 | 53 | 57.1 |
| **Developing Asia** | 3,165 | 75 | 23.6 |
| China | 1,037 | 34 | 32.5 |
| India | 473 | 13 | 27.2 |
| South Korea | 493 | 8 | 15.6 |
| Other Asia | 1,162 | 21 | 17.7 |
| **Middle East** | 577 | 20 | 35.3 |
| Turkey | 186 | 3 | 17.0 |
| Other Middle East | 391 | 17 | 44.3 |
| Africa | 499 | 12 | 25.0 |
| **Central and South America** | 1,452 | 21 | 14.4 |
| Brazil | 816 | 9 | 11.0 |
| Other Central/South America | 636 | 12 | 18.6 |
| **Total Developing** | 5,693 | 129 | 22.6 |
| **Total World** | 30,555 | 403 | 13.2 |

# FOSSIL ENERGY

## Introduction

Fossil energy resources are currently the backbone of the U.S. energy system, both for stationary (power plant and industrial), and non-stationary (transportation) applications. Their continued availability in the short term is critical to the health and growth of the U.S. economy. Their reasonable prices establish the ground rules for the competition among different fuels. The different fossil fuels will not always fill the same roles in the future that they do in the current economy because they have highly variable resources bases, but there will be critical select applications for which each of the fossil fuels will always remain the best among all of the alternatives. Ensuring energy security requires making the needed fuels available in quantities (and therefore at prices) that will maintain U.S. economic security.

This section outlines the current situation with respect to the major fossil fuel groupings, and provides information on current applied research priorities within DOE's Office of Fossil Energy. Reviewing the situation and the midterm applied program objectives is important in order to understand what we are currently doing. This helps focus attention on the many unknowns that will be the objectives of any fundamental research program.

## Coal

### *Supply and Demand*

Of the three main fossil fuels used today (coal, petroleum, natural gas), coal has the largest reserves, both domestically and worldwide (Table 2.1). Domestic use totaled 24 EJ (23 Quads) [EIA 2001], while domestic recoverable reserves totaled 6,100 EJ (275 billion short tons) [EIA 2002]. At current rates, the U.S. has over 250 years of existing recoverable coal reserves.

There are several varieties of coal (lignite, subbituminous, bituminous, and anthracite) with varying qualities, such as heat and ash content. Bituminous and subbituminous coals are most often used for electricity production, while some power plants use lignite. Anthracite is of higher quality and used more for coking operations or other industrial needs. Over 89% of coal in the U.S. is consumed by electric generators, with 3% by coking plants and 8% by other industrial users.

**Table 2.1. Fossil Fuel Reserves (EJ)**

| | U.S. | Global |
|---|---:|---:|
| Coal | 6,084 | 24, 082 |
| Petroleum | 124 | 5,788 |
| Natural Gas | 192 | 5,731 |

*Source: EIA 1999*

Coal is mined from the surface or underground, depending on the geology and topography of the coal seam. Each mining process has its advantages and disadvantages. Surface mining is generally more disruptive to the environment. Underground mining is more dangerous and expensive. The country can be divided into three main coal regions: Appalachia, the Interior, and the West (Figure 2.1). The largest production of coal is through surface mining in the West (Figure 2.2).

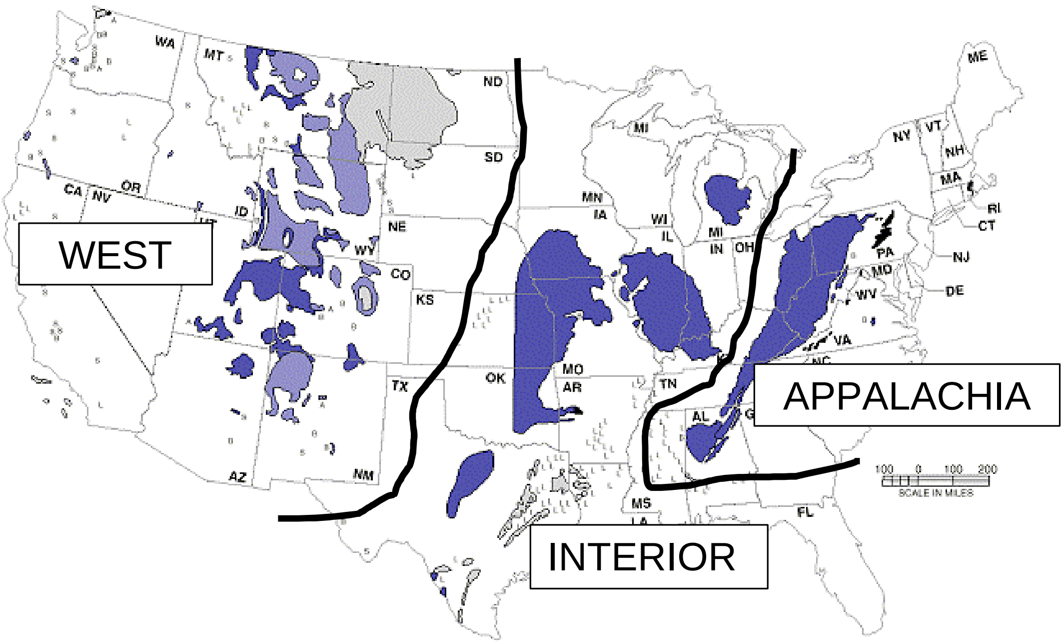

**Figure 2.1. U.S. Coal Regions**
*Source: EIA 1999*

Sulfur content is a key parameter for coal (Table 2.2); the quality varies with regional location. High-sulfur coal is found largely in the Interior and Appalachia and low-sulfur in the West (Figure 2.3). While this figure shows recoverable reserves, the demonstrated reserve base is roughly double this amount.

Because of emissions regulations and mining costs, the move towards the use of western low-sulfur, surface-mined coal has increased greatly. Between the years 1989 and 2001, western coal production increased 71%, while Appalachian coal production declined 8% and Interior production declined 25% [EIA 2002].

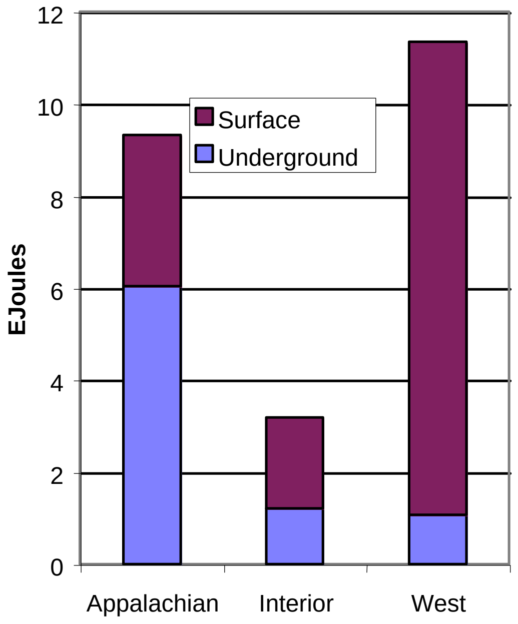

**Figure 2.2. Year 2000 U.S. Coal Production by Region and Mining Type**
*Source: EIA 1999*

**Table 2.2. Average $SO_2$ Content of Different Classes of Coal**

| | lb/MBtu | g/MJ |
|---|---|---|
| Low Sulfur | 0.6 | 0.26 |
| Med Sulfur | 1.9 | 0.81 |
| High Sulfur | 4.5 | 1.93 |

*Source: EIA 1999*

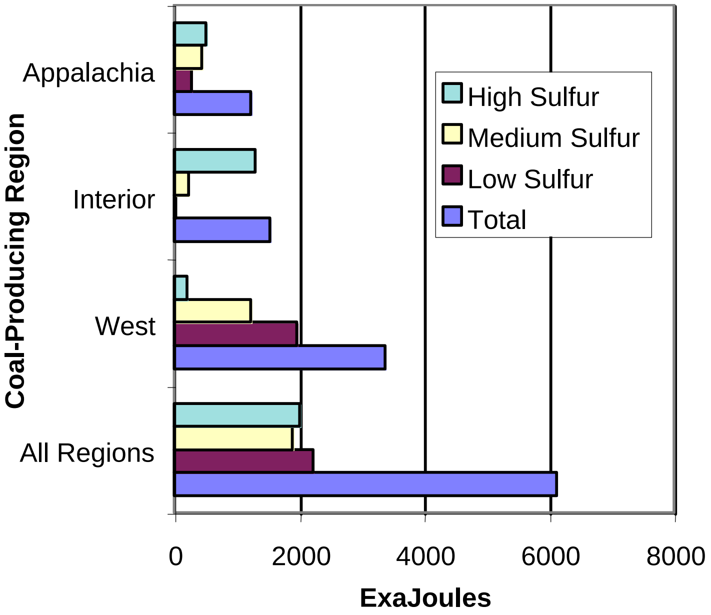

**Figure 2.3. U.S. Estimated Recoverable Coal Reserves**
*Source: EIA 1999*

### *Issues*

The key long-term issue for use of coal is the nature and volume of emissions. These include $SO_2$, $NO_X$ and the amount of greenhouse gas emitted. Coal contains 24.4 g Carbon/MJ, while natural gas emits just 13.7 g C/MJ. Nuclear or renewable sources release essentially net zero greenhouse gases (depending on the amount of fossil fuel used in their production).

Other contaminants in coal are also a major issue. Sulfur emissions from all fuels have been regulated for years, with recent proposals from the U.S. government to lower the limits by 73% by the year 2018. Mercury is another air pollutant, deriving largely from the use of coal. The U.S. government's "Clear Skies" proposal will reduce mercury emissions 69%, from the current 48 tons to 15 tons. Though coal combustion produces significant amounts of nitrogen oxides, it is not the major source of $NO_X$ within the U.S. All fossil fuels produce $NO_X$, especially petroleum from motor vehicles. However, within the electricity sector, coal is a significant source of emission of $NO_X$, especially if power plants have no treatment equipment. Current regulations and lawsuits are forcing utilities to install selective catalytic reduction (SCR) or other equipment to reduce $NO_X$ emissions.

With large domestic reserves and low cost, coal could contribute much more to our nation's energy supply, if emissions issues are resolved. However, since coal is a solid, it is more difficult to use for transportation or distributed energy.

### *Research Areas*

Since carbon oxidation is the major source of energy derived from coal, and greenhouse gas production is of greater concern, significant mechanisms to reduce or eliminate the emissions of gaseous $CO_2$ is worthy of long-term research. According to *Clean Energy Future*s [Interlaboratory Working Group 2000], there are numerous ways of removing $CO_2$ from the atmosphere and of storing it or keeping anthropogenic carbon emissions from reaching the atmosphere. Six carbon sequestration methods were described in a recent report [DOE SC/FE 1999]:

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

Some of these options are available today. $CO_2$ injection into geological formations as part of enhanced oil recovery has been practiced for decades, although the long-term performance of these formations at retaining $CO_2$ for longer periods has never been tested. Oil and gas fields that retained gaseous hydrocarbons for thousands of years may be expected to retain $CO_2$ equally well. Deep aquifers without documented caprock containment may be abundant but of uncertain capacity to retain $CO_2$. Since 1996, Statoil in Norway has sequestered annually about 1 million tonnes of $CO_2$ in sandstone 1000 meters beneath the North Sea, which is equivalent to about 3% of Norway's emissions [Herzog 2001]. Other near-term options are available because they can provide important secondary benefits, such as improving ecosystems during reforestation. However, most options involve long-term carbon management, requiring considerable research to ensure their successful development and acceptance. Because carbon capture and sequestration will require additional energy use, additional power use will be needed, perhaps provided by additional coal. David and Herzog show a 9-15% energy penalty for carbon capture and sequestration from coal-fired power plants in the year 2012, with an increase in cost of $2.9 to $6/GJ (1.04 to 2.16¢/kWh) [David and Herzog 2000]. These costs translate into $18 to $32 per tonne of $CO_2$ avoided. While promising, deep sea and geological storage options have constraints, including environmental impacts, safety, and duration of storage.

Continued improvements in efficiency and environmental acceptability could enable coal to establish a growing role in both the U.S. and worldwide energy portfolios, while still pursuing the goals of a clean energy future. The DOE Office of Fossil Energy has developed an applied research agenda "Vision 21 EnergyPlex" [FETC 1999], a new approach to 21st century energy production from fossil fuel-based systems. 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 resulting emissions of air pollutants. Improvements in combustion, filtration, gas separation, and chemical conversion will all play a role. These technologies will build on current research in integrated-gasification combined-cycle power plants and fuel cell advances to create tertiary cycle systems incorporating fuel cells, gas turbines, and steam turbines. If successful, this multi-product approach may achieve efficiencies approaching 60-80% after the year 2015. This increase is well above the typical 33-35% efficiencies from today's conventional coal-fired power plants.

## Gas

### *Supply and Demand*

Natural gas is relatively abundant, both in the U.S. and worldwide and relatively inexpensive. Domestic proven reserves stand at 192 EJ, while consumption in the year 2000 was 25 EJ (23.4 Quads). Global supplies are also large, with estimated reserves at 5,700 EJ (5,300 TcF). Compared with use of other fossil fuels, natural gas consumption is growing the fastest (Figure 2.4), increasing 21% between the years 1990 and 2000. Overall, production of electricity is the fastest growing use of natural gas, increasing 52% from the years 1990 to 2000.

Beyond proven reserves of 192 EJ (177 TcF), conventional gas has a domestic resource base of 670 EJ (616 TcF). Non-conventional sources, such as tight sands, coal-bed methane and Devonian shale, also have large resource bases and could become more widely used depending on prices of other competing energy sources. Other non-conventional sources show even more potential. Methane hydrates, found in permafrost regions and the seafloor, are believed to have massive potential (Table 2.3).

According to the *National Energy Policy* [NEPDG 2001], while the resource base that supplies today's natural gas is vast, U.S. conventional production is projected to peak as early as the year 2015. Increasingly, the nation may have to rely on natural gas from non-conventional sources, such as tight sands, deep formations, deep water, and gas hydrates. Also, many resources are in environmentally sensitive areas requiring use of less intrusive technologies.

Most gas is transported and delivered through pipelines. Offshore and onshore wells deliver gas through systems that span the country (Figure 2.5). A small amount of gas is delivered to the U.S. by liquid natural gas (LNG) ships.

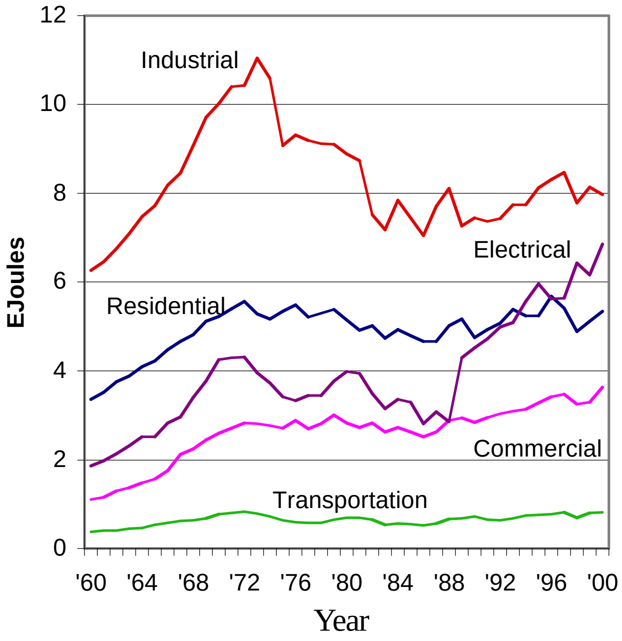

**Figure 2.4. U.S. Natural Gas Consumption (EJ)**
*1989-2000 Electrical includes non-utility generation.
*Source: EIA 2002a*

Prices for natural gas were fairly steady through the year 2000 (Figure 2.6). However, prices were extremely volatile in the years 2000 and 2001, returning to historical levels in the year 2002. High prices were attributed partly to the low prices for gas and oil in the year 1998, which reduced the amount of new drilling. Once prices rose, drilling accelerated. There is some question whether this market volatility will be ongoing or an aberration.

**Table 2.3. U.S. Natural Gas Resource Base**

| | EJoules |
|---|---|
| Conventional (High and Low Quality) | 670* |
| Unconventional (Coalbeds, Tight Gas, Devonian Shales) | 560* |
| Gas Hydrates | 350,000** |

* Technically recoverable domestic resource base
** Mean estimate of U.S. hydrate resource base
*Source: IWG 2000*

### *Issues*

Natural gas is relatively clean, emitting only 13.7 g C/MJ and essentially no $SO_2$. The main concern is the amount of $NO_x$ that is emitted during combustion with air, although recent improvements in technology have greatly reduced these amounts. Natural gas is not as easily stored as a liquid and has contributed only a small role in the transportation sector.

Since natural gas is the cleanest of the fossil fuels and relatively available domestically, it is expected to be the preferential fuel for new growth. To increase gas consumption significantly, the infrastructure (pipelines, storage fields, and distribution systems) to support this growth will need to be built.

Natural gas could become more widely used as a transportation fuel. If fuel cells are to be used, hydrogen must be separated from the other components of fuel. This is easier generally with natural gas. (Natural gas is already used in hydrogen manufacturing for oil refining.) However, advances in reformers may increase the feasibility of liquid fuels, lessening the advantage of natural gas. Alternatively, if liquid fuels remain preferable for transportation (either in conventional engines or fuel cells) and petroleum supplies diminish, then natural gas could be converted to liquids. Conversion of gas to liquid is available, although the process is not as economically feasible as current use of oil.

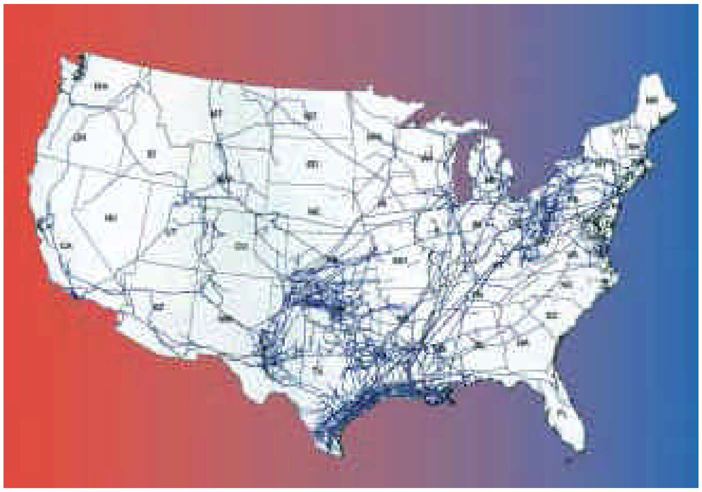

**Figure 2.5. Gas Pipeline Infrastructure**
*Source: NEPDG 2001*

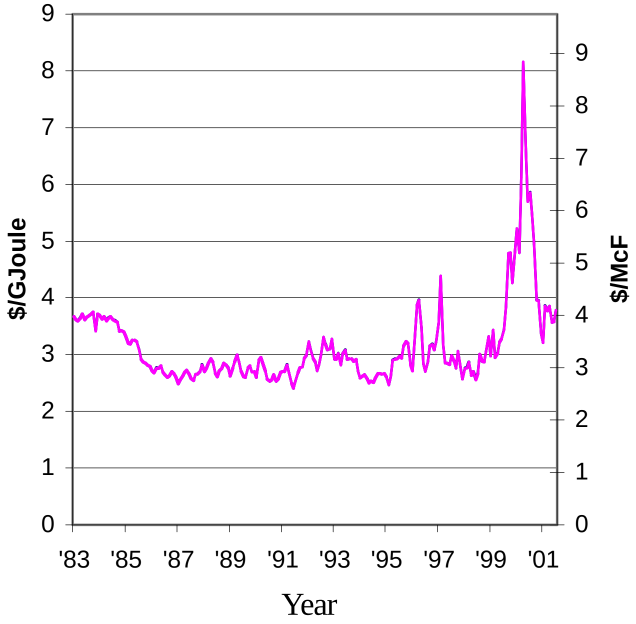

**Figure 2.6. U.S. Average Citygate Gas Prices**
*Source: EIA 2002b*

### *Research areas*

Natural gas and oil will both benefit from advanced exploration, drilling, and recovery methods. The *National Energy Policy* [NEPDG 2001] outlines many of the applied research areas that will enhance oil and gas discovery, drilling, and recovery:

- advanced, more energy-efficient drilling and production methods;
- 3-D seismic technology, to increase greatly the success rate by enabling geologists to use computers to better determine the location of oil and gas before drilling begins;

- deep-water drilling technology, to enable exploration and production of oil and gas beneath the ocean's surface, at depths over two miles;
- high-powered lasers, to drill for oil and gas; and
- highly sophisticated directional drilling, to enable drilling of wells at long horizontal distances from the drilling site.

Recent Office of Fossil Energy applied oil and gas program workshops identified detailed basic research needs, applicable to both the oil and gas sectors.

The workshop on fundamental applied research identified the following areas that require additional research:

- enhanced oil recovery - methods to modify oil in-situ, fundamental physical and chemical properties of reservoir fluids and rock, dynamic process characterization and monitoring, and multifunctional chemicals;
- reservoir characterization - improved interwell imaging, integrate core, logging and seismic data, improve capability for processing real-time datasets;
- drilling, completion and stimulation - smaller drilling systems, improved fluid-flow identification, downhole separation technology, and diagnostics of tight/unconventional gas.

The diagnostic and imaging workshop recommended four applied research and development (R&D) topics:

- understand and overcome the limits on seismic resolution, including acquisition and processing, hardware, and sampling theory;
- data fusion or integration, both static and dynamic data at multiple scales and from multiple sources, including knowledge management and visualization;
- pre-stack and elastic inversion, including 3-component data and processing framework; and
- shear wave imaging, integrated seismic-electromagnetic, and single well imaging system.

The workshop on accessing deep formations defined applied R&D needs for deep drilling:

- advanced smart drilling systems - real time data transfer and real time data instrumentation, and rig operator decision support system;
- drilling diagnostics and sensor systems - downhole diagnostics drilling parameters including data validation, weight torque on bit, and state of bore hole analysis; and
- drilling and completion fluids - economic tests and simulators to determine drill fluid contribution to well-bore stability.

According to *Clean Energy Future*s [Interlaboratory Working Group 2000], a significant amount of undiscovered domestic conventional and non-conventional (see Table 2.3) gas sources are accumulated deeper than 15,000 feet in widely differing geologic settings. Several technology challenges must be overcome to exploit deep resources, including better ways to detect commercial volumes of gas using surface-based sensing and use of advanced materials for drilling at high temperatures and pressures at extreme depths. 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, the location, sedimentary relationships, and physical characteristics of methane hydrates must be determined. In addition, production approaches for disassociating the methane from the cage of water ice molecules in the hydrates must be developed. Hydrates are quasi-stable, so releasing the methane requires either reducing the pressure or increasing the temperature (or both) of the material. Among other methods of gas production, the feasibility of using depressurization by a drilling well in hydrate reservoirs [Ji et al. 2001] is being studied.

Hydrogen production, along with capture and sequestration of the carbon from natural gas, would enable natural gas to be a long-term source of energy for the U.S. and worldwide. Sequestration and separation technology must become more economically feasible, and the political will to reduce carbon emissions must occur on a broad scale.

Gas-to-liquid research may lower the cost for natural gas to be used as a liquid fuel for critical sectors such as transportation. This will open up domestic resources to replace petroleum if supplies tighten. Also, it can allow distant natural gas fields, such as on the Alaska North Slope, to use existing oil pipelines.

## Oil

### *Supply and Demand*

Domestic supplies of petroleum are small compared with the large annual use. Current domestic reserves stand at 124 EJ (22 GBarrels), while consumption in the year 2000 was 41 EJ (39 Quads or 7.2 billion barrel or 20 million barrel per day) [EIA 2001]. The current worldwide availability of oil reserves (5,800 EJ) compared to the rate of consumption (158 EJ) suggests only 35 years worth of remaining supply. This is a misleadingly small number since reserve growth has consistently paralleled consumption over the last century related, to improved technology and thus recovery rates. Unquestionably, much of the future oil supply is located in politically volatile areas (Figure 2.7 and Figure 2.8). In addition to the reserves already identified, the U.S. Geological Service (USGS) estimates undiscovered resources of another 4,000 EJ (720 billion barrels) [USGS 2002] worldwide.

Crude oil production has declined in the U.S. for years. OPEC (Organization of the Petroleum Exporting Countries) was the dominant supplier through the 1970’s, reducing production in the 1980’s to maintain higher prices. Other suppliers entered the market after prices increased in the 1970’s. Their production has grown at a slower pace in the 1990’s (Figure 2.9).

In addition, other potential sources (such as heavy oil, tar sands, or gas-to-liquids) are available at current or higher prices and through advances in technology. Over 3 trillion barrels of these non-conventional fuels are estimated as available (17,000 EJ), with the most significant deposits in Canada and Venezuela. In addition, coal-to-liquid technologies and oil shale deposits dwarf conventional oil resources [EIA 2002].

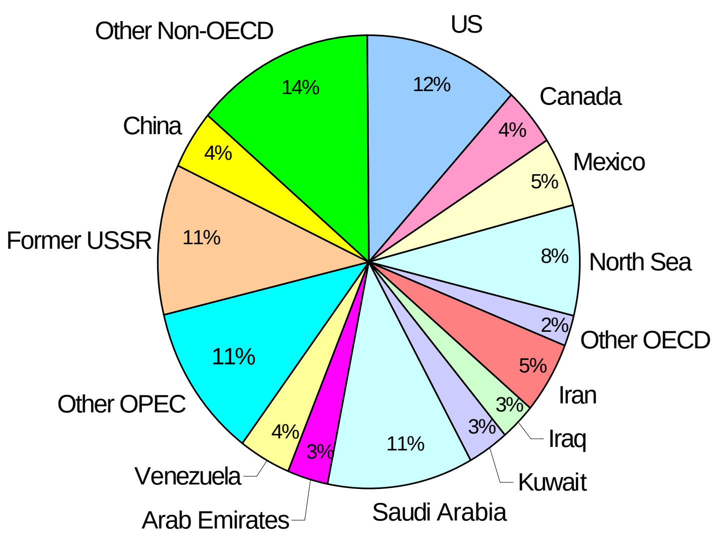

**Figure 2.7. Year 2000 Crude Oil Supply (158 EJ or 77 million barrels per day)**
*Source: EIA 2002*

Oil is currently the dominant fuel for transportation, providing over 96% of the energy used in that sector. The current transportation infrastructure supports a liquid fuel supply. Any change in supply source would require a major transformation in the transportation industry. Oil is also used to a smaller extent in other sectors (Table 2.4) Distillate fuel is used for home heating and industrial combustion turbines, while residual fuel is used for industrial and electrical boilers. Oil is also used as a feedstock to petrochemicals and plastics.

### *Issues*

Domestic conventional supplies have been insufficient to meet U.S. consumption for several decades. The U.S. must import over half of the total oil supply needed, challenging national security and jeopardizing the trade balance. In the year 2000, the U.S. imported 58% of the oil consumed, costing $116 billion. The major suppliers are shown in Figure 2.7. U.S. production has been declining since 1970, and a turnaround is not expected. Oil must be recovered from more complex and inaccessible fields, with the depletion in more accessible locations. Technology improvements (such as steam injection, horizontal drilling, and 3-D seismography) have extended the life of many oil fields. Some fields within the U.S. have not been exploited, but their use is very controversial (e.g., Arctic National Wildlife Refuge).

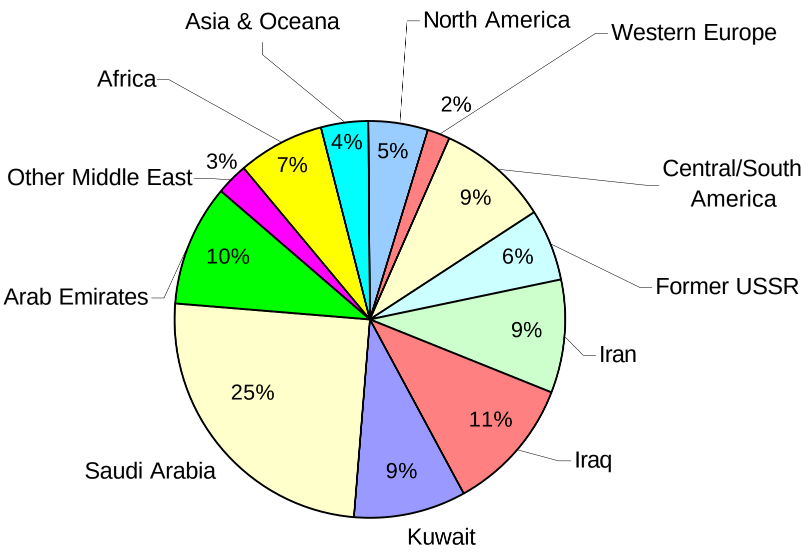

**Figure 2.8. Global Petroleum Reserves (5,800 EJ)**
*Source: EIA 2002*

As with all fossil fuels, $CO_2$ (20.4 g C/MJ) is emitted during combustion. Since most oil products are used in nonstationary applications, capturing these at the source is difficult. Rather, $CO_2$ may need to be se-

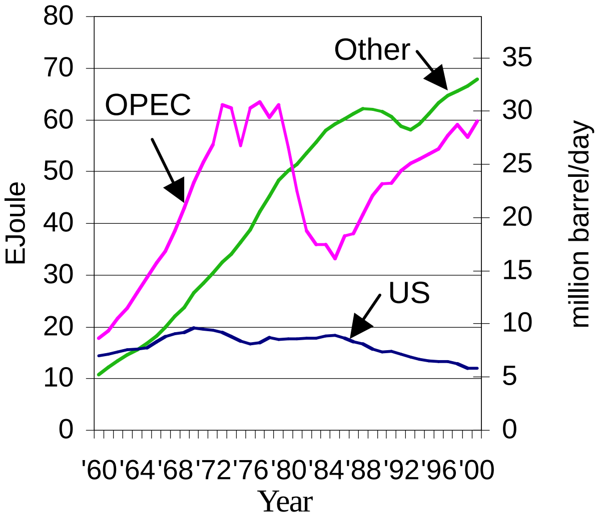

**Figure 2.9. Crude Oil Production**
*Source: EIA 2002*

questrated through withdrawal from the general atmosphere. Other notable pollutants from oil combustion include $NO_X$, which contributes to low-level ozone formation. Specific fuels (e.g., diesel fuel) also produce pollution as particulates.

With all forms of transportation heavily dependent on oil, disruption of the supply may create broad economic problems. The Strategic Petroleum Reserve provides short-term oil supplies, but longer-term relief may require more diverse sources of transportation fuels.

***Research areas***

Many of the opportunities for research in oil production are the same as described earlier for natural gas. In addition, there is research ongoing in improvements to refinery operations that lower the energy usage, such as use of inorganic membranes for improved separation of gases and recycle of waste streams. Advanced research and development (R&D) includes computational methods to improve catalyst development and experimental evaluation. Such improvements and R&D can increase the use of domestic, low-quality oils that are difficult or expensive to refine today.

**Table 2.4. Year 2000 U.S. Refined Petroleum Products Consumption**

| | EJ | Million Barrel/Day |
|---|---|---|
| Motor Gasoline | 17 | 8.5 |
| Jet Fuel | 4 | 1.7 |
| Distillate Fuel | 8 | 3.7 |
| Residual Fuel | 2 | 1.0 |
| Other | 10 | 4.8 |
| Total | 41 | 19.7 |

*Source: EIA 2001*

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## NUCLEAR FISSION ENERGY

### Current Status

The U.S. has 104 commercial reactors operating at the present time. All are one of two variations of light-water reactors (LWR)s. There are 69 pressurized water reactors of the type produced by the former Babcock and Wilcox, Combustion Engineering, and Westinghouse Corporations and 35 boiling water reactors produced by General Electric. Commercial nuclear reactors currently produce about 20% (8.5 EJ in the year 2000) of the electricity generated by American utilities. As shown in Figure 3-1, this fraction increased dramatically in the latter part of the 20th century, but has been relatively constant in recent years. Nuclear fission accounted for 1.44% of electrical generation in 1970, 11.0% in 1980, and 20.5% in 1990. For purposes of comparison, the nuclear electric fraction in 2001 for several other industrialized nations was: United Kingdom - 23%, France - 77%, Belgium - 58%, Germany - 31%, and Japan - 34%.

The most recently commissioned nuclear plant began commercial operation in 1993. The modest further increases in U.S. nuclear generation shown in Figure 3-1 since that time have arisen primarily from two factors: (1) improved plant capacity factors, as shown in Figure 3-2, and (2) small power upgrades at existing plants. Power upgrades ranging from 1.4 to 6.3% at 57 reactors were approved by the U.S. Nuclear Regulatory Commission (NRC) between 1977 and 2001. These upgrades added approximately 2000 MJ/s (MW) electrical ($MJ/s_e$) capacity equivalent, roughly the equivalent of two new nuclear power plants. The upgrades were made possible largely through the application of state-of-the-art instrumentation, and auxiliary equipment upgrades. Upgrades comprising another 1600 $MJ/s_e$ are expected to be approved during the next 5 years. During this same period, the Tennessee Valley Authority is planning to carry out the necessary work to restart Watts Bar Unit 1, which has been shutdown since 1985. This project will add another 1065 $MJ/s_e$ nuclear capacity. Thus, in the absence of either orders for new

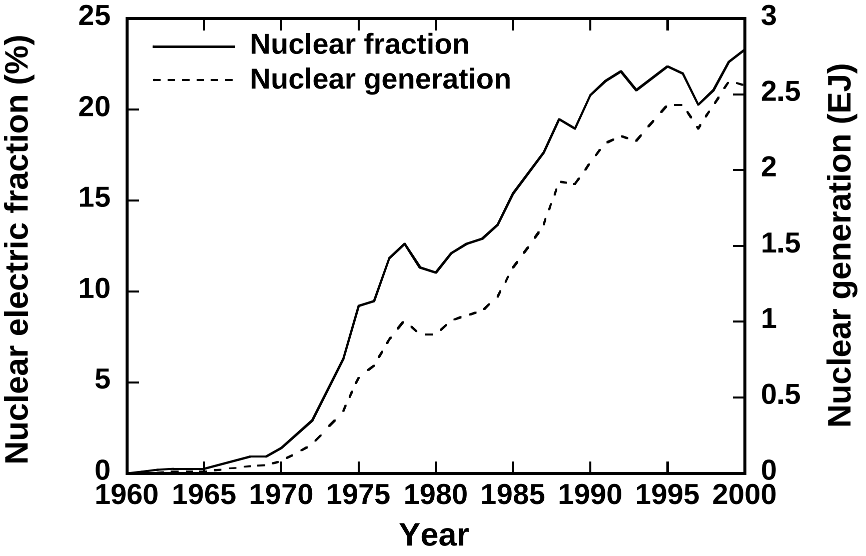

**Figure 3.1. Nuclear power contribution to electrical generation in the U.S.** Both the fraction of utility-generated electricity and the total nuclear electric generation is shown.

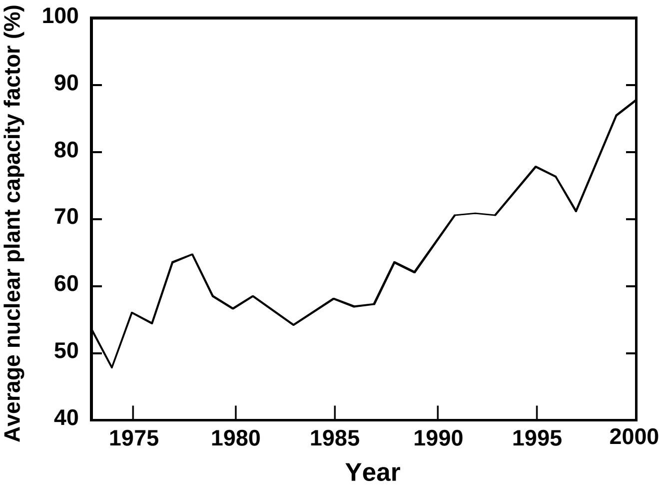

**Figure 3.2. Average nuclear power plant capacity factor for units in the U.S.**

construction or unexpected difficulties, nuclear electrical capacity is expected to increase by 2.5 to 3% over the next 5 years. In this case, the proportion of electricity produced by nuclear fission is likely to remain slightly above 20%.

Future growth of nuclear energy is a goal of the present administration and the Department of Energy. A program called NE-2010 (http://www.ne.doe.gov/planning/NucPwr2010.html) , the Nuclear Power 2010 Initiative, was announced in February 2002 to facilitate the building of a new nuclear electric generating station by 2010. Such a plant likely would incorporate one of the standardized designs that have already been reviewed by the NRC and as such will involve only modest extension of current technology. These designs provide major improvements in safety and in system simplification by reducing dependence on power-driven complex equipment for emergency core and containment cooling. Direct-cycle high temperature gas-cooled reactor (HTGR) designs are also candidates. They are extensions of HTGR technology that have predicted major improvements in reliability and simplification through elimination of the intermediate cooling systems and the potential for water-graphite interactions.

The DOE also has led a long-term international program intended to lead to the design of the next generation of nuclear reactors, the so-called Fourth Generation designs. The Generation-IV (http://gen-iv.ne.doe.gov/) effort is primarily defined by several technological and economic goals, notably including, higher reliability and efficiency, a high level of inherent safety, financial life-cycle advantages over other technologies, low financial risk, and waste minimization. The intent is to reduce the net cost of nuclear-generated electricity while improving public acceptance of nuclear reactors. The *Generation-IV Technology Roadmap* has recently defined the most promising reactor concepts for long-term development under this program, and has defined the research and development required to commercialize those concepts.

The *Generation IV Roadmap* has a major fuel cycle component that is likely to be incorporated into the Advanced Fuel Cycle Initiative now being developed by DOE’s Office of Nuclear Energy, Science and Technology (NE). Processing of fuel is a large element in this part of the Generation-IV program. The *Generation-IV Roadmap* also indicated the desirability of developing technology that is sufficiently flexible to be used for multiple purposes, such as production of hydrogen, providing process heat, and desalination.

Many of the issues preventing the expansion of nuclear energy are social and political. The Generation-IV framework is designed to identify and address many of these issues with respect to reactors to be deployed after 2020. An additional and often major objection to even continuation of nuclear power has been concern about the need for long-term storage of spent fuel in the absence of a designated permanent disposal site. In 2002, the Congress and the President approved the Department of Energy developing a license application for the Yucca Mountain waste disposal site. The successful implementation of this decision may improve the acceptance of nuclear power. The major technological issues related to spent fuel storage have been investigated, and ongoing research in this area is being funded by DOE primarily in the Office of Civilian Radioactive Waste Management, although some will be done in the Environmental Management Science Program, being transferred to OS, and BES presently does support some basic research on issues relating to radioactive waste isolation.

The other major impediment to the expansion of nuclear energy in the U.S. is economic, probably the major reason no new U.S. plants have been built for decades and perhaps the highest hurdle for new designs to overcome. A recent study by the International Energy Agency (IEA) on the relative competitiveness of natural gas, nuclear power, and coal among members of the Organization for Economic Cooperation and Development (OECD) examined various operating costs, capital costs, plant decommissioning costs, and the costs of waste disposal. The IEA concluded that in terms of operating costs, nuclear power plants are competitive against coal and natural-gas-fired generation units. Natural-gas-fired units averaged 2.2-4.1 cents/kWh, coal plants 1.9-3.3 cents/kWh, and nuclear 0.8-3.2 cents/kWh. The fuel costs for a nuclear power plant are significantly lower than those for coal or natural gas plants. However, construction costs, which are strongly dependent on the cost of capital, are another matter. In capital-intensive industries such as electricity generation, interest rates play a key role in determining the relative economics of different generation fuel sources. The capital cost of a new nuclear unit is substantially higher than that for a comparable fossil unit. In addition, due to their higher construction costs, the relative cost of nuclear power plants is more sensitive to interest rates than are the costs of coal or natural gas plants. Using recent values for French-built pressurized-water reactors, capital costs averaged $1,636/kW at 0%, $1,988/kW at 5% interest, and $2,280/kW at 10% interest. Care must be taken when using costs, as well as construction times, in other countries. Government roles, as well as financing approaches, differ significantly and therefore these numbers are not directly transferable to the U.S.

Construction costs are also sensitive to the time of construction. Although nuclear power plants have been built in as little as 4 years, the IEA study noted that the average construction time for U.S. plants completed after the Three Mile Island accident was 12 years. The increased construction time resulted from the need to incorporate improvements in safety identified by the accident, inefficient management of the construction, as well as to cope with the drastic drop in the rate of increase in electricity demand following the OPEC (Organization of the Petroleum Exporting Countries) embargo. In recent years, new plants have been constructed in Japan and Korea to regulatory standards somewhat similar to U.S. requirements in a 4 to 4 1/2 year time frame. The IEA study concluded that nuclear energy was competitive in more than one-half of the OECD (Organization for Economic Cooperation and Development) countries analyzed at the 5% rate, but was not competitive at 10%. Currently approved and certified reactor concepts hold promise of shorter construction times, and expedited construction is a goal of the Generation-IV design concepts. However, until new reactors can be shown to meet these expectations and are constructed and begin operation there will remain considerable hesitancy and skepticism by the electric utility industry as to whether the environment and legal structure in the U.S. will allow such expedited construction.

The major resource issue associated with nuclear power is the supply of uranium. Current best estimates of proven uranium reserves are adequate for more than 50 years at the current rate of consumption, with about three times that amount in so-called speculative reserves. There is also an extensive potential uranium resource available in seawater if the technology can be developed to economically extract it. In addition, weapons-grade uranium and plutonium from military stockpiles in the U.S. and Russia is being made available for use as reactor fuel. This material is highly enriched, at over 90% U-235. Similarly enriched plutonium (93% Pu-239) can also be used in mixed-oxide fuel. Conversion of just the highly enriched uranium will provide about 15% of world reactor requirements for more than 20 years. The spent-fuel reprocessing that is being carried out in Europe and Japan provides further feedstock by recycling unburned U-235 and Pu-239, although this is being done on a very limited basis. If the level of reprocessing was expanded, all these sources might provide adequate feedstock for nuclear reactor fuel for at least 100 years, although the economics of reprocessing are not currently favorable.

If reprocessing and other technologies mentioned above do not expand, but nuclear power does, then more uranium must be utilized. Significant levels of uranium enrichment capacity exist in the U.S., France, Germany, Netherlands, United Kingdom, Japan, Russia, and China. The commercial technologies used are gaseous diffusion and gas centrifuge. The gaseous diffusion process was developed during World War II, and plants using this process tend to be older, but still account for about 60% of installed capacity. The more recent gas centrifuge process is more efficient. Compared to gaseous diffusion, it consumes only about 20% of the electricity per unit of uranium enriched. Excess capacity has worked to keep the cost of enrichment relatively stable in recent years, with the U.S. closing down some of its oldest, World War II vintage gaseous diffusion plants. The remaining U.S. enrichment capacity is adequate for almost twice the current nuclear fuel demand in the U.S.

## Future Research Needs

The IEA economic study evaluated and compared existing, not future technologies. Expectations are that future nuclear power plants will see significant efficiency gains through programs like the Generation-IV effort. Of course, some gains may also be expected for competing technologies. The most significant gains could be achieved by nuclear power if the safety features of new designs increase social acceptance, and if the predicted lower construction costs also can be realized. Design safety issues are heavily addressed in each of the Generation-IV design studies.

Another major focus of the Generation-IV designs is increased thermal efficiency in the nuclear steam supply system (i.e., obtaining more electrical energy per unit thermal energy). As a result, higher operating temperatures are desired, which increases the demands on structural material performance. In March of this year, DOE Office of Nuclear Energy, Science, and Technology (NE) and the Office of Basic Energy Sciences (BES) sponsored a workshop to bring together experts from the reactor materials and design community with fundamental materials scientists to identify research and development needs and opportunities to provide optimum high temperature nuclear energy system structural materials. The format of the workshop was structured around the reactor concepts proposed as part of the *Generation-IV Nuclear Energy System Roadmap* in order to define relevant research needs, while at the same time making an effort to identify research needs that cut across designs.

Among the many materials R&D areas identified at the workshop, the following areas appear to be the most critical for advancing Generation-IV concepts:

- Research on advanced ferritic-martensitic and martensitic steels that allow for increased temperature of operation for liquid-metal and supercritical water concepts while improving toughness at lower temperatures. Issues include stability of oxides in oxide-dispersion-strengthened materials, basic microstructural and microchemical changes, and phase stability at high temperatures. This will require the use of irradiation facilities, which are few in the U.S. and may require going overseas. This first area should identify the work necessary to develop a limited number of the most promising candidates for the irradiation research in the following five areas.

- Development and fundamental understanding of radiation performance of refractory alloys, ceramic composites, and coatings for high and very high temperature concepts.

- Research to improve radiation performance of austenitic stainless alloys including resistance to void swelling, embrittlement and stress corrosion cracking. This research should also examine other alloys employed in present and near-term deployment plants, as well as consider non-radiation environments for these materials.

- Development of new high-temperature superalloys that are tailored for radiation environments (e.g., low nickel contents and controlled phase stability)

- Fundamental and applied understanding of the complexity of radiation damage in engineering alloys, including austenitic, ferritic, ferritic-martensitic, refractory metals, and ceramic materials.

- Developing a more detailed understanding of the radiation-induced complex, non-equilibrium microstructural and chemical evolution which occurs at the nanoscale, leading to changes in plasticity, corrosion and fracture processes.

All six of these areas could benefit from basic research and all six of them could equally benefit from applied and developmental research. The responsibility for basic research that underpins these six areas properly belongs to BES.

Some additional basic research areas that warrant consideration include:

- irradiation assisted stress corrosion cracking and aqueous corrosion
- irradiation induced embrittlement
- mechanisms and modeling for the degradation of radioactive waste packages
- welding and joining (Temperbead repair, laser welding, underwater welding)
- nondestructive evaluation and condition monitoring
- mechanical behavior, predictive modeling and computer simulation
- radiation effects
- heat transfer
- complex multiphase fluid flow
- human performance
- neutronics
- reprocessing methods

A final issue related to both safety and efficiency is reactor fuel performance. In order to minimize refueling frequency, some advanced designs have proposed exposing fuels to higher burnups. In addition to reducing the downtime for refueling, these schemes also reduce the amount of high-level waste created. Some of these designs involve fuels more highly enriched in U-235 than current LWR fuels (possibly increasing concern about diversion of nuclear materials). Achieving higher burnup will increase the effects of radiation damage to the fuel (e.g. swelling and cracking) and higher operating temperatures will further challenge the stability of the fuel. In order to reach the desired fuel performance goals, advanced oxide or carbide fuels may be required. There is limited experience with the coated-particle fuel form used in advanced gas-cooled reactor designs. German-fabricated fuel has performed well in irradiation tests, but experience with U.S.-fabricated fuel has been mixed. Thus, issues related to fuel performance also warrant further research. Higher fuel burnup and higher fuel temperatures will also increase the demands placed on fuel cladding or fuel coatings that constitute the engineered barriers to fission product escape. Significant improvements in fuel performance may not be possible without concomitant improvements in the radiation resistance of the structural materials mentioned above.

## Summary

Nuclear energy provides somewhat more than 20% of electricity in the U.S., 35% in the European Union, 24% in all OECD countries - about 16% of electricity worldwide. The importance of this power source may increase due to concerns of greenhouse gas emissions from fossil-fired (coal, oil and natural gas) plants used to produce 65% of the world's electricity. For example, according to a recent OECD report, OECD power plant emissions of carbon dioxide without nuclear power would be about one-third higher than they are at present. This is an annual savings of 1.2 billion tons of carbon dioxide, or about 10% of total $CO_2$ emissions from energy use in the OECD.

It is difficult to envision a scenario in which the Kyoto Protocol emission target of a 700 million ton reduction in carbon dioxide emissions in OECD countries by 2008-2012 (relative to 1990 levels) can be achieved without either a significant reduction in electrical production or an increase in the use of nuclear-generated electricity. This realization is part of the basis for the current debate on nuclear power in countries such as Germany and Sweden that have initiated plans to shut down their nuclear plants, and for plans in the U.S. and elsewhere to increase nuclear capacity by reviving the nuclear industry. The initial steps in that revival are the extension of useful life of the present generation of nuclear plants and the deployment of new plants in the near term. Similar efforts to extend the lives of existing plants are being pursued overseas and an International Near Term Deployment plan has been formulated to achieve goals similar to the U.S. NE-2010 program as an adjunct to the International Generation-IV planning. For the longer term, the Generation-IV International Forum (http://gen-iv.ne.doe.gov/intl.html), with the U.S. DOE in a lead role, is identifying the reactor designs, and accompanying research needs for the next generation of reactors that will further improve reactor safety, reliability, thermal efficiency, and waste management.

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# RENEWABLE AND SOLAR ENERGY

Energy sources that are replenished by nature, with human intervention, and within a relatively short time period after their use are defined as "renewable energy." Their replenishment can range from being instantaneous to requiring decades. In contrast, fossil-based energy resources require millions of years for their formation and cannot be effectively replenished. The U.S. Energy Information Administration generally includes the following sources as "renewable": conventional hydroelectric, geothermal, wind, solar, biomass, and waste. To further define these categories, the following information is offered:

- Conventional hydroelectric power is distinguished from pumped storage hydroelectric power since the latter is a net energy consumer.

- Solar includes both solar thermal and photovoltaic (PV) sources.

- Biomass includes organic matter produced by biological photosynthesis (lignocellulose from trees, corn and other energy crops, wood and woody plants, algae and other photosynthetic organisms, food by-products, etc.) that can be converted to fuels and chemicals by fermentation or thermal processing.

- The waste energy stream includes methane and other flammable gases recovered from landfills, and various solid waste forms that are burned to produce electricity or thermal energy.

Hydroelectric, wind and solar power do not produce any greenhouse gases at the point of energy generation, whereas combustion of biomass and waste and fermentation of biomass produces $CO_2$. As long as an equivalent amount of biomass is regrown through photosynthesis, there is no net increase of $CO_2$ in the atmosphere as a result of burning or fermenting biomass. Depending on the source and application, geothermal sources may also release greenhouse gases, as well as other noxious gases such as hydrogen sulfide.

Renewable energy resources can contribute to all the major energy sectors in the U.S., including electricity (25%), transportation fuels (28%), residential and commercial space heating (19%), and industrial process heat (28%). The central goal for renewable energy is to become competitive with fossil energy.

## Global Energy Issues

To properly discuss the role of renewable energy for future U.S. energy needs it is necessary to discuss the future global energy picture. The world population is expected to grow to 10-11 billion people by the year 2050, and this growth will be concentrated in the developing counties. This population growth, together with the standard of living goals for these developing countries, will impact the emission of greenhouse gases to an extent that will limit the use of fossil fuels everywhere in the world, including the U.S., and require huge amounts of carbon-free energy. The numbers are quite staggering, and have been summarized by M.I. Hoffert [Hoffert 1998, Hoffert et al. 2002]. The essence of this analysis is that a population of 10-11 billion by year 2050, an increase in the average world GDP of 1.6%/yr (historical average), counterbalanced by a decrease of 1%/yr in the energy consumption per unit of GDP because of expected increases in the efficiency of energy utilization, produces an expected energy consumption in year 2050 of 28 TW (or 888 EJ/yr) (1 TW = 31.7 EJ/yr). The present world energy consumption rate is about 13 TW (412 EJ/yr). Although fossil fuel resources and proven reserves are huge (40,000 EJ for oil plus gas and 180,000 EJ for coal, enabling their possible use for about 50 years for oil and gas and 275 years for coal), their use will possibly be severely restricted by the problems of $CO_2$ emissions. If the $CO_2$ concentration in the atmosphere is to be restricted to 550 ppm in 2050 (twice the pre-industrial value; the present level is 325 ppm), then by 2050 this will require the availability of 20-30 TW of carbon-free power. This is appreciably more than the total world energy consumption today! Furthermore, even if no restrictions on $CO_2$ emissions were implemented, but rather the present rate of decrease in carbon intensity of energy utilization continues (at a rate of -0.56 kg C/yr/watt), then 10 TW of carbon-free energy will be required in 2050 – also a huge and daunting requirement.

The available global renewable resources are estimated to be: (1) hydro: 4.6 TW total, 0.9 TW practical, and 0.7 TW already installed; (2) wind: 50 TW total on land, 2-4 TW practical on land; higher if oceans are utilized; (3) biomass: 5-10 TW total (not considering land required for food production and utilizing 100% of the cultivatable crop land for energy production), practical: unknown possible restriction due to water supply; (4) solar: 1.2 x $10^5$ TW total; practical: 600 TW (60 TW at 10% conversion efficiency) ( to generate 12 TW of solar power at 10% efficiency would require 0.1% of the worlds land mass). These numbers suggest that the best long range renewable resource that could provide the required carbon-free energy is solar, whether implemented as biomass or as photovoltaic or advanced solar conversion technology. However, breakthroughs and disruptive technology are required to achieve such a level of implementation. A similar case for the need for daunting amounts of carbon-free power can be advanced based on sustainability arguments even in the absence of greenhouse gas effects.

**Electricity from Renewable Energy Sources**

As shown in Figure 4.1, the total net electrical production by electrical utilities from renewable energy sources has remained essentially constant since about the year 1975, with hydroelectric power accounting for nearly 99% of the renewable contribution. Values for the various renewable components in the year 2000 were: hydroelectric, 0.91 EJ; geothermal, 7.2 x $10^{-4}$ EJ; wind, <1.8 x $10^{-4}$ EJ; solar, <1.8 x $10^{-4}$ EJ; wood, 2.52 x $10^{-3}$ EJ; and waste, 4.7 x $10^{-3}$ EJ. Since the consumption of electricity has increased by about 57% since the year 1975, the fractional contribution of renewable energy sources to electricity production by utilities has been declining, as shown in Figure 4.2.

As shown in Tables 4.1 and 4.2, nonutility power producers utilize renewable energy sources to a greater extent. In the year 2000, electrical utilities generated 10.8 EJ and nonutility producers 2.82 EJ of electricity. The absolute and relative contribution for all sources is shown in Table 4.1, and the renewable sources are compared in Table 4.2. Since the nonutility producers have less hydropower and little nuclear power, their relative use of both fossil fuels and other renewables is higher than the utilities.

Increasing hydroelectric generation is the most rapid way to grow the renewable component of electricity production. It is estimated that 60 GJ/s of undeveloped hydroelectric power is available in the U.S. Assuming a 50% capacity factor, 60 GJ/s of hydropower would add 0.95 EJ of energy annually, more than doubling the current contribution. Tapping into this potential capacity would involve three approaches: upgrading equipment at existing hydropower facilities, adding generating equipment at existing dams that are not so equipped, and developing new projects. The development of new hydroelectric projects may involve a trade-off between the potential elimination of generating facilities that produce greenhouse gases and the impact of new dams on waterways and marine life.

As shown in Figures 4.1 and 4.2, other renewable energy sources have not yet made a significant contribution to electricity production by U.S. utilities, despite substantial R&D efforts initiated after the oil shocks

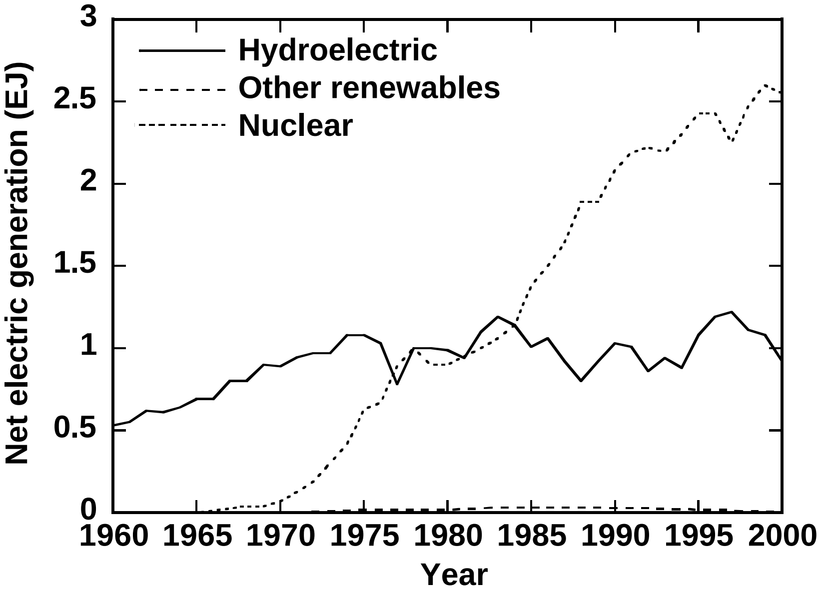


**Figure 4.1. Electrical production by utilities from all renewable energy sources with conventional hydroelectric shown separately from other renewable sources.** Nuclear energy, the other $CO_2$-free electric source is included for comparison.

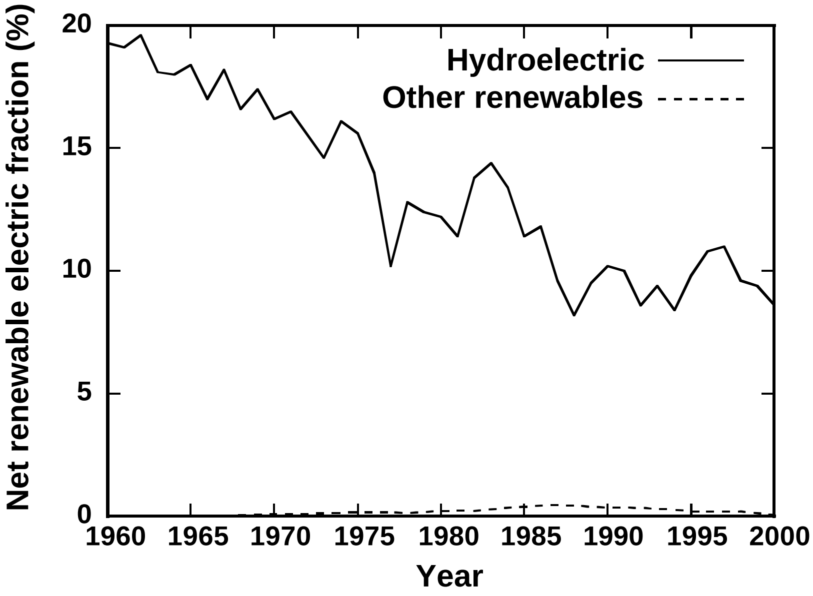


**Figure 4.2. Fractional contribution of conventional hydroelectric power and other renewable energy sources to total electrical production by utilities.**

## Table 4.1. Electrical Energy Production and Fractional Contribution from Various Sources for Utility and Nonutility Power Producers

| Electrical energy source | Electrical utilities | | Nonutility producers | | Fraction of total electricity (%) |
|---|---|---|---|---|---|
| | Energy (EJ) | Fraction (%) | Energy (EJ) | Fraction (%) | |
| coal | 6.09228 | 56.129 | 0.98064 | 34.803 | 47.107 |
| oil | 0.26028 | 2.398 | 0.13176 | 4.676 | 2.246 |
| natural and other gas | 1.04328 | 9.612 | 1.15812 | 41.101 | 10.637 |
| total fossil | 7.39584 | 68.139 | 2.27016 | 80.567 | 59.989 |
| nuclear | 2.53944 | 23.396 | 0.1746 | 6.196 | 19.028 |
| hydroelectric | 0.91044 | 8.388 | 0.07812 | 2.772 | 6.862 |
| geothermal | 0.00072 | 0.007 | 0.0504 | 1.789 | 0.136 |
| wood | 0.00252 | 0.023 | 0.13968 | 4.957 | 0.381 |
| waste | 0.00468 | 0.043 | 0.08388 | 2.977 | 0.252 |
| wind | 0.00018 | 0.002 | 0.01764 | 0.626 | 0.047 |
| solar | 0.00018 | 0.002 | 0.00288 | 0.102 | 0.009 |

## Table 4.2. Relative Fraction of Various Renewable Sources to Total Electrical Production from Renewable Sources for Utility and Nonutility Producers

| Electricity source | Electrical utilities (%) | Nonutility producers (%) |
|---|---|---|
| hydroelectric | 99.091 | 18.428 |
| wood and waste | 0.758 | 52.498 |
| geothermal | 0.114 | 24.161 |
| solar | 0.019 | 0.737 |
| wind | 0.019 | 4.177 |

of the early 1970s. This research reduced substantially the cost of some renewable power sources (currently, 3-5 cents/kWh for wind and 25-30 cents/kWh for PV) . A major limiting factor for adoption of these sources is the cost and practicality of electrical energy storage and integration into the power grid.

The peak in the utilities renewable energy production curves in the year 1987 is due to a peak in geothermal power that year. The total non-hydro renewable contribution to electricity production in the year 2000 was less than 1%. A very substantial increase in these values is required if they are to contribute significantly to the reduction in greenhouse gas production in the near future. A combination of technical and natural obstacles must be overcome to make this a reality.

The present relative importance of renewable energy sources increases when total energy production is considered. Total geothermal energy production includes geothermal heat pumps and direct thermal energy use. Similarly, the solar energy component includes space and water heating. Wood burned for space heating is the largest single component. In the year 2000, renewable energy consumption (without hydroelectric) was 3.50 EJ, or 5.2% of total energy production. Of this, wood, waste and alcohol was 3.09 EJ; geothermal was 0.30 EJ; solar was 0.066 EJ; and wind was 0.048 EJ. The alcohol was that blended with gasoline for use as a motor vehicle fuel.

## Research and Development Issues

### *Wind*

Due to ongoing improvements, wind is the renewable energy technology closest to being economically competitive today. In the year 1999 worldwide wind capacity increased by 36% to 13,400 MJ/s, with Germany, the U.S., and Spain contributing over 40% of the increase. Some projections indicate that the local contribution of wind to electrical capacity could reach up to 10-20% in some regions. Such a significant market penetration would require addressing the impact of the intermittent output of wind through modification of systems operation, hybrids with other technologies (e.g., gas turbines), and energy storage. Near-term R&D is needed for higher towers, lightweight blades with advanced airfoil designs, direct-drive systems, advanced power conversion devices, and durable and lightweight structural components. Overall, the greatest impediment to widespread use of wind power is a lack of sites that offer consistent and adequate volume and velocity of winds. If high reliability is needed from the wind generation site, the cost of a backup system such as a gas turbine adds significantly to the net cost of electricity.

Studies at the National Renewable Energy Laboratory (NREL) have shown that, if windmills are sited at 5% spacing, which is about the optimal spacing of windmills so that they do not obscure one another, and if no excluded, environmentally-sensitive lands or urban areas are covered, then approximately 0.4 TW of wind power can be produced in the U.S. This amount of energy, though small compared to the 3 TW that is currently consumed domestically from all energy sources, is comparable to the entire current U.S. electricity consumption.

With respect to electric wind power potential, 27% of the earth's land surface is rated as class three, representing lower available velocity. A class four rating represents land where sited windmills are economical (~3-5 cents/kWh of electricity production) by having a mean wind speed at a certain height above ground. The proposed use of class-three-rated land for windmill siting requires advances in wind turbine technology to make these lower wind velocity areas economical in the next 50 years. Adding up all class three and four land surfaces, and considering practical siting constraints, results in approximately 2 TW of electrical power potential from terrestrial wind.

The offshore electrical power potential of wind is larger than 2 TW and, in some cases, such installations make geopolitical sense. However, going far offshore would be required to realize a needed demand of 10-20 TW of carbon-free power primarily through wind-generated electricity. Getting the power generated offshore to the land-based regions where it is needed to meet demand can result in transmission losses. In addition, the impact of removing energy from the atmosphere through the number of windmills necessary to produce the level of power needed might have a negative impact on weather and other atmospheric conditions. For example, to produce the 0.4 TW of domestic electricity needed from the available class four wind resource areas in North Dakota, a state with high potential for using wind energy, 50% of the energy in the atmosphere would have to be removed through an exhaustive installation of windmills. It is not clear what the impact of such a drastic measure would be.

Exploitation of wind-generated electricity on a large scale is challenging in the U.S. for another set of important reasons. The wind resource is not located where the power demand is. Most of the U.S. population resides outside of major wind producing areas. The grid cannot currently handle the level of power that might be produced by wind. Furthermore, wind is a relatively mature technology, but as an intermittent source demands an accompanying energy storage system. The use of compressed air storage in the windfarm is probably the best way, from a physics point of view, to provide the storage capacity and thereby convert an intermittent resource into baseload power. The penalty of including storage is about 1 cent/kWh, so such an approach becomes interesting when wind electricity is about a factor of two lower in cost than it is now. Hence large scale use of wind power poses challenges in assessing possible limitations that might arise due to extracting significant amounts of energy locally out of the natural atmospheric circulation, in handling the potential load with the structure of the grid, and in finding effective storage methods to convert intermittent power to baseload power.

The effectiveness of wind turbines depends on the interaction of the blade with the air flow at its surface, a challenging problem in basic fluid dynamics. Turbulence at the surface deforms the blade locally as it turns, which in turn disturbs the local air flow. Advanced numerical methods in computational fluid dynamics are needed to accurately predict the fluctuation aerodynamic forces, blade deformations, and vibratory responses. A second basic research problem is the structural performance of the turbine blade. New blade materials and composite fabrication techniques are needed that combine light weight, high stiffness, and long lifetime (> $10^9$ cycles) with low manufacturing costs. These goals can be achieved through improved understanding of composite materials behavior and fatigue mechanisms. Finally, the variability in local wind conditions leads to intermittent power production that can be accommodated if it is known a few days in advance. A better understanding of mesoscale atmospheric processes is needed to forecast average and turbulent wind flow fields over complex terrain in the lower 200 meters of the atmospheric boundary layer with high accuracy three days in advance.

### *Geothermal*

Geothermal power is cost competitive at good quality sites, and the installed geothermal electrical capacity has increased from 500 MJ/s in the year 1973 to the current 2800 MJ/s. However, the number of such sites is limited, with most being located in the western U.S., Alaska, and Hawaii. Geothermal wells are a versatile energy source that are currently being used to produce electricity, to heat greenhouses through direct thermal use applications for geothermal heat pumps, and in aquaculture. The geothermal resource in the U.S. is huge, with over 40,000 Quads of energy potential. However, 90% of this potential is at low temperatures (<150°C or <300° F) and much is inaccessible as a result of lack of water, low permeability soils, and environmental concerns. To access these 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. Materials performance problems exist due to the corrosive nature of steam at some locations.

Geothermal energy makes important contributions to the energy mix in certain regions, including the western U.S. and regions of the Asian-Pacific and central Europe. Some nations, such as the Philippines, produce a significant portion of their electricity from geothermal sources. Other nations, such as Iceland, use geothermal heat directly for space heating and industrial processes. The use of geothermal heat pumps in the U.S. has increased significantly in recent years and, in fact, holds the largest potential for increasing the geothermal component of the total energy mix because the development is not dependent on special high-temperature geothermal regions. Nonetheless, large expansion of geothermal utilization is likely to be dependent on reducing both development costs and uncertainty. Major costs involved in finding and developing geothermal energy are associated with exploration and drilling. Reduction of drilling costs is an important target for applied research. However, the better location of drilling targets would be another way to reduce costs and requires advancement of the basic sciences involved in exploration. Uncertainty in resource size and performance acts as a hindrance to development, since developers prefer surer targets. Improving the understanding of reservoir performance mechanisms through basic research would be useful to lower this uncertainty and thereby increase the rate of development.

### *Photovoltaics*

The solar constant is 1.76 x $10^5$ TW, hence, there is ample solar energy potential. From the 1.2 x $10^5$ TW of solar energy that strikes the earth's surface, a practical siting-constrained terrestrial solar power potential value is about 600 TW. The numbers range from very conservative estimates of 50 TW to optimistic estimates of 1500 TW, depending on the land fraction devoted to power generation. A good number to use for onshore electricity generation potential is probably 600 TW. Thus, for a 10% efficient solar farm, at least 60 TW of power could be supplied from terrestrial solar energy resources. For calibration, photosynthesis currently supplies 90 TW globally to make the biosphere run, so the amount of power available from the sun is very large (see Fig. 4-3).

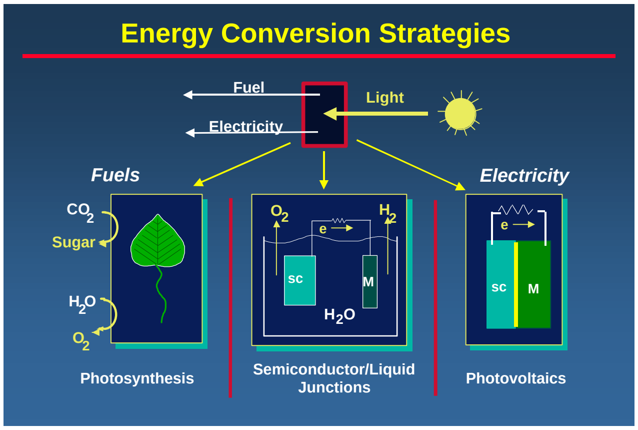


**Figure 4-3. Energy conversion strategies for converting solar energy to usable energy.**

The land area that is required to produce 20 TW of carbon-free power from solar energy is 0.16% of the earth's surface, or 5 x $10^{11}$ $m^2$. Producing 3 TW with a 10% efficiency solar cell farm would require covering 1.7% of the land in the U.S. The size of even this project (comparable to the land devoted to the nation's interstate highways) should not be underestimated (see Fig. 4-4). For example, if a 10% efficient solar energy conversion unit was installed on every home rooftop in the entire U.S., only 0.25 TW of power would be generated. Nevertheless, this requires about a factor of 100 less land than current biomass technology and similarly less land than using wind to generate equivalent amounts of power.

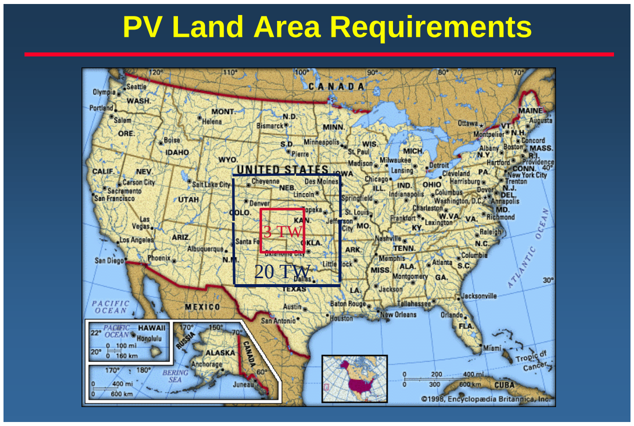


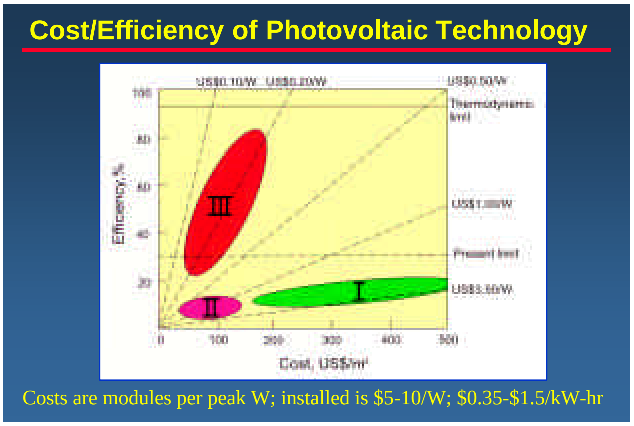
**Figure 4-4. Boxes showing land area requirements to produce 3 TW or 20 TW of photovoltaic energy at 10% efficiency.**

The efficiency of photovoltaic devices has been increasing steadily. Nevertheless, current technologies all lie on a relatively common cost/watt scale. The underlying reason for this roughly equal cost/watt trade-off is that the photovoltaic materials now available suffer from the same fundamental physical limitations. Large-grain, pure materials, with a long lifetime capable of making efficient solar cells, are costly to produce. Alternatively, cheaper materials with smaller grain sizes have grain boundaries that act as recombination sites, resulting in inefficient solar cells. A similar trade-off is found for organic ("plastic") photovoltaics. If pure inorganic single-crystal materials, like silicon and GaAs, are replaced with much cheaper organic materials, the materials are inherently disordered and therefore are cheaper but more inefficient. The net result is that one can ride anywhere on this cost/watt trade-off scale, but nevertheless end within a factor of 20%.

Use of disruptive technologies is one approach to reducing the cost/watt trade-off. Further discussion on these approaches is found at the end of the next section on advanced direct solar photoconversion.

### *Advanced Direct Solar Photoconversion*

Direct solar photoconversion is the process whereby the energy of solar photons is either converted directly into fuels, chemicals, or materials starting from simple and renewable substrates such as water, $CO_2$, and $N_2$, or the photons are converted directly to electricity. These processes require photoactive organic, inorganic, or biological molecules or materials that can absorb a large fraction of the solar irradiance and drive the chemical reactions that produce the fuels, chemical, materials, or electricity. The latter photoconversion process that produces electricity can be distinguished from photovoltaic conversion based on solid state semiconductor p-n junctions by the fact that molecular photochemical and/or electrochemical processes are involved in photoconversion.


Cost/Efficiency of Photovoltaic Technology

Costs are modules per peak W; installed is $5-10/W; $0.35-$1.5/kW-hr

**Figure 4-5. Cost/efficiency of photovoltaic technology.**

Three branches of science and technology can be defined for solar photoconversion: photoelectrochemistry, photochemistry, and photobiology. They all depend upon photoinduced charge generation (i.e., electrons and positive holes) followed by efficient positive and negative charge separation at various types of interfaces that ultimately produce oxidation-reduction (redox) chemistry. Photoelectrochemistry involves semiconductor-molecule interfaces, photochemistry involves molecule-molecule interfaces, and photobiology involves biological interfaces with other biological and non-biological molecules.

Fuels produced by solar photoconversion are derived from endoergic reactions wherein the photon energy is stored as chemical free energy in the reaction products. Extremely important examples of this process are hydrogen from photolytic water splitting, and methane, methanol, or ethanol from the reduction of $CO_2$ by water. The later can be termed "artificial photosynthesis" since biological photosynthesis uses the same reactants of $CO_2$ and $H_2O$ to form biomass and $O_2$. However, the term "artificial photosynthesis" is also applied more generally to all fuels and chemical products produced via solar photochemistry. The photoactive molecules and materials used to create and separate electrons and holes and to drive the appropriate redox chemistry are semiconductors (inorganic or organic) in photoelectrochemistry, molecular structures in photochemistry, and biological structures (e.g. *in vivo* water-splitting blue-green algae or *in vitro* reaction centers) in photobiology. Some photoconversion reactions can also be exoergic, such as photooxidation of organic molecules to make higher value products or to destroy organic pollutants and the formation of hydrogen from organics or biomass using photosynthetic bacteria.

The best reported conversion efficiency (rate of $H_2$ free energy produced/solar power in) for the photolytic splitting of water by semiconductor structures is about 12%. It was achieved using a monolithic tandem cell structure consisting of two series-connected p-n junctions of GaAs and $GaInP_2$ with metal catalysts deposited on the anodic (oxygen evolving) and cathodic (hydrogen evolving) sides of the layered structure. However, the cost of this cell is very high, and the use of such high-efficiency tandem cells is usually reserved for space applications. Photobiological production of hydrogen by photosynthetic blue-green algae has recently been achieved without the usual poisoning of the algae by the evolved oxygen. However the conversion efficiency is very low (< 1%).

For photoconversion to electricity, the conversion systems can be configured so that the separated electrons and holes produce a photocurrent and photovoltage, rather than drive chemical reactions. The best systems to date are based on photoelectrochemical cells (semiconductor-molecule interfaces), producing power conversion efficiencies that have been as high as 17% . A recently developed cell that looks potentially promising is based on the dye sensitization of nanocrystalline titanium dioxide (a nontoxic and cheap paint pigment) films by adsorbed dye molecules. This potentially very cheap cell shows conversion efficiencies in the laboratory of about 10%. Another potentially major advantage of photoelectrochemical cells for electric power is that they can be configured to store the photogenerated electricity by using part of the photogenerated power to charge a third electrode in the cell , which can discharge in the dark. Such a cell becomes a photochargable battery that can deliver power day and night.

The grand challenge for direct solar photoconversion is to discover and develop conversion systems that exhibit combinations of efficiency and capital cost per unit area that result in delivered electrical or stored chemical energy at very low cost , and furthermore are stable and robust under operating conditions for 10-15 years. To reduce the cost of installed photoconversion systems to $0.20/ peak watt of solar radiation, a cost level that would make them economically very attractive in today's energy market, would require that they have a capital cost of about $\$100/m^2$ together with a conversion efficiency of about 40% or a cost of $\$2/m^2$ and an efficiency of 15 %. The power produced by such systems would yield electrical power at a cost of about 1-2 cents/kWh or $H_2$ at about 2-4 cents/kWh free energy equivalent. Such combinations of cost and efficiency require truly disruptive technologies that do not exist at the present time. However, these goals do not violate any fundamental scientific principles and are not beyond the realm of possibility.

One important strategy to attain these goals is to identify approaches that produce ultrahigh conversion efficiency. Present photon conversion devices based on a single threshold absorber, including solid-state semiconductor photovoltaics, all operate within a regime wherein the ultimate thermodynamic conversion efficiency is limited to about 32% with unconcentrated sunlight. In this regime, the photogenerated electrons and holes are in thermal equilibrium with the phonons (quantized lattice vibrations) of the light-absorbing material. This means that the energy of photogenerated electrons and holes in excess of the threshold energy (i.e., the bandgap) is not utilized for useful work, but rather is converted into heat. Furthermore, in this regime photons less energetic than the threshold energy are not absorbed. Recent research has shown that the equilibration of electrons and phonons (also referred to as hot electron cooling) can be slowed by 1 to 2 orders of magnitude in semiconductor quantum dots, quantum wells, and related nanostructures. Other researchers have shown that conversion efficiencies above the 32% limit may be achieved by the formation of resonant impurity bands in photoelectrodes produced from quantum dot solid arrays that can absorb two sub-bandgap photons to create one electron-hole pair, photon up-conversion whereby a higher energy photon is produced from two lower energy photons, and photon down-conversion whereby two smaller energy photons are produced from one energetic photon. Another approach to achieving high conversion efficiency, also yielding a theoretical thermodynamic maximum of about 65%, is to use multiple bandgap absorbers in a cascaded tandem configuration. In the limit of threshold absorbers matched to the solar spectrum the limit is 65%, but two tandem bandgaps as estimated to yield about 40% conversion and 3 tandem bandgaps to yield about 50% conversion.

Another approach to meet these cost/watt goals is to find chemical methods (referred to as disruptive technologies in the Photovoltaic overview) to fool the inexpensive photoconversion materials (like polycrystalline, nanocrystalline, and organic materials) into performing as if they were expensive single crystals, without actually incurring the costs to grow the expensive crystals themselves. This approach involves chemically treating these inexpensive materials with "solar paint" so as to fool their grain boundaries or interfaces into thinking they are part of the periodic crystal that this material is trying to emulate (e.g., see Fig. 4-6). A related strategy is to produce so-called interpenetrating networks. Use of such networks relaxes the usual constraint in which the carriers that are excited must exist long enough in their excited states to traverse the entire distance of the cell. Instead, the materials consist of a network of interpenetrating regions. There are two examples of these approaches that are just emerging; neither of them are economically or technologically viable today, but they seem like good approaches in the long run to achieve the difficult cost goals of 1-2 cents or less per kWh. In the end, this approach will have to be as cheap as painting your house and mass-produced like sheets of plastic or photographic film.

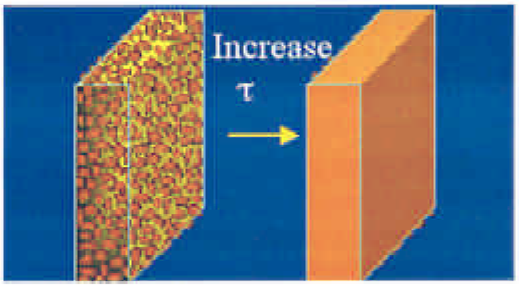


**Figure 4-6. Solar paint passivates grain boundaries in inexpensive photovoltaics, causing them to perform like expensive single crystal materials.**

Direct formation of fuels will also require development of inexpensive, robust, and efficient thermal and/or photochemical catalysts for the formation of such fuels from abundant, inexpensive, recyclable chemicals. Important targets include the direct photochemical splitting of water into $H_2$ and $O_2$, catalysts that individually reduce water to hydrogen and oxidize water to oxygen which could be used either in an integrated fashion with photoelectrochemical devices or in a modular fashion with PV systems, and catalysts that allow effect the reduction of $CO_2$ to organic fuels (such as methanol or methane) or which utilize $H_2$ with $CO_2$ to form hydrocarbon fuels.

All the various possible strategies for high efficiency, low cost, high stability and long lifetime solar photoconversion systems must be examined and compared to find the optimum system(s) to achieve the important goals described above for producing stored chemical free energy in fuels or electricity from renewable resources. This is particularly vital since photoconversion is a direct solar conversion process that utilizes the largest available renewable energy resource and has the potential to operate with ultrahigh conversion efficiencies and with very low cost materials.

### ***Biomass***

Biologically-based strategies for providing renewable energy can be grouped into two major categories:

- those which use features of biological systems to convert sunlight into useful forms (e.g. power, fuels) but do not involve whole living plants as we know of today, and
- those involving growth of plants and processing of plant components into fuels and/or power.

Given the current state of knowledge and uncertainty, it is far too soon to declare either of these "the winner" (or loser), and there are legitimate "homerun" possibilities in each category. It is recommended that both categories be pursued aggressively with roughly equal aggregate research effort considering the U.S. portfolio of energy-related research as a whole.

Among current and foreseeable plants and plant material, lignocellulosic biomass has the greatest potential for energy production and oil displacement in light of scale, cost, energy balance, and ecological considerations. Thus it is appropriate to focus consideration of research involving plant-based energy systems on cellulosic biomass. This should be done with an appreciation for the merit of well-justified research on plant types that are not foreseeable at this time, or to develop properties that circumvent the limitations of current non-lignocellulosic plants. It may be observed that the potential importance of biomass in meeting human needs currently met by non-sustainable resources depends on both technical and societal factors, a feature common to most renewable energy sources.

The domain of plant-based energy production can be categorized into work focused on plant production, and work focused on conversion of plant products. Both are very important and a roughly equal aggregated effort seems appropriate, considering the U.S. portfolio of energy-related research as a whole. Long-term improvements can be expected in the development of both biomass resources and the conversion technologies required to produce electrical power, fuels, chemical, materials, and other bio-based products. For example, the world's first biomass gasification system, in which wood chips were converted to gas to fire a boiler, was successfully operated. 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 bio-energy. 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 co-firing of coal-fired power plants provide opportunities for learning-by-doing.

R&D challenges and opportunities can be classified into three broad areas. The first concerns terrestrial plants and algal systems in fresh and salt water. Productivity of plants in adverse environments (saline and degraded soils, high aridity ecozones) is very limited, yet to mitigate increasing human use of good soils and maintain ecosystem values such as biodiversity requires sustained long-term efforts. There may also be possibilities to increase the efficiency of photosynthesis and photosynthate storage. Recent work has started to elucidate not just the mechanism of photosynthesis but to also understand the molecular architecture of light harvesting and water splitting. Genomics first of Arabidopsis, and now underway for tree species (*Pinus* and *Populus*, already a candidate energy crop), and cereals (*Oryza* spp) will enable many aspects of the genome to be both understood and possibly manipulated to increase biomass production in total, of selected plant polymers and intermediates, and eventually to control both the composition and the macromolecular architecture. Work on *Rubisco* the enzyme that transports almost 2/3 of all carbon dioxide in the atmosphere through the leaves of plants each year, may be one area that could pay off as well. With a more broad genetic understanding of plants both physiology and pathway work can benefit from technology transfer from societies large investment in biomedical technologies. In depth understanding of plant cell wall architecture, and of the mechanism and control of storage polymers in plants, detailed molecular mechanisms by which cellulose, other plant cell wall polysaccharides, and other key polymers are synthesized and deposited would facilitate novel materials, chemicals, and fuels from the biosphere.

The second area concerns post-harvest conversion of plant materials to fuels, chemicals, and materials. Currently the major biomass conversions use either thermochemical or bioconversion approaches. Gasification to molecules such as carbon monoxide and hydrogen, the components of synthesis gas, can generate desired fuels, chemicals and materials with suitable catalysts. Biological conversions require prior reduction of the plant cell wall polymers to simple molecules that are often monomers to the plant polymers such as glucose, xylose, and phenyl propane units from lignocelulosics, or complex and novel oligomers from starches or other storage compartments of plants.

Biotechnology offers a superb array of new and rapidly developing tools to advance our basic understanding of plants, enzymes and organisms. The advances during the past half-decade in the "omics" (genomics, proteomics, and metabolomics) also show great promise for continuing our understanding of the ways microbial cells live, multiply, and produce needed chemicals and materials. In addition, X-ray crystallography, neutron diffraction, molecular mechanics computer modeling, and electronic and atomic spectroscopies serve scientists to probe protein structure and elucidate chemical function. The "pull" from biomedical research needs will provide a steady stream of research innovations and tools available for use in other applications.

A third area of effort is in biomimetic construction of materials that today are unavailable naturally but could have preferred engineering properties at macroscales in textiles, the built environment, and many other areas. An opportunity is the development of new carbohydrate based nanoscale materials. Features unique to certain carbohydrate compounds induce them to self assemble into nanostructural materials that could have use as highly selective, structurally defined catalysts, and other applications. However, there is little known about how the structural features present in individual molecules translate into the ultimate shapes adopted by supramolecular structures. Once understood, carbohydrate based systems could develop with predictable properties as new nanomaterials for the future.

Looking back, a major issue is that our dependence on nonrenewable feedstocks for fuels, chemicals, and materials has been a direct function of our inability to manipulate complex polymeric molecules that compose plant resources to products other than food, feed, fuel, fiber and non-engineered wood polymers. Much about the current knowledge about plant cell wall structure, function, components, and physical and chemical properties has been derived as a way to obtain specific product performance targets – not necessarily to design at the molecular level the myriad of products that plant resources could provide if the science base were in place. Some chemical and materials technologies that are still in the market place are more than 100 years old. In plants, the interpenetrating networks of polymers and their complex biological synthesis suffer from great natural variability due to weather, geographic conditions, soil quality, water availability, and a host of other factors. Tools to unravel such complexity and provide the needed science base are now available and should be used to enable renewable resources for fuels, chemicals and materials to serve society's needs for the future.

The “green revolution” increased remarkably the productivity of several grains thus decreasing concerns of the world’s ability to feed a growing population. In fact, in 20 years, cumulative world agricultural production increased by 91% in developing countries and by 32% in the developed world. Significant increase in productivity was obtained through conventional genetics and a variety of inputs to fertilize the soil and control pests. This revolution includes environmental legacies of degraded and contaminated soils and water bodies.

The “green revolution for the next 50 years” needs to address productivity and selectivity of desired products to increase the efficiency of land and water use, while maintaining and improving soil, water, and air quality for future generations. This can only happen with a significant increase of the science base from which breakthroughs will emerge. It will require the integration of the body of knowledge from related areas such as genomes (sequencing and functional), developing and mining databases for information on properties and functions, and “omics”, currently mostly developed for human life sciences, and applying these tools to plant science, enzymes, bacterial, fungal, and microbial consortia and photosystems, and other organisms at a much increased pace as well. Integrative, quantitative, experimental, and computational approaches will bring new knowledge, novel methods, and innovative technologies to engender a better understanding of complex biological systems and processes for renewable fuels, chemicals, and materials for the 21st century.

Promising research directions 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. The yield of many field crops appears to be approaching upper limits. By contrast, it seems likely that the application of modern technology can lead to several-fold increases in the amount of biomass produced by woody species per unit area per unit time. Advances in this area are expected to come, in part, from advances in understanding the basis of plant growth and development. Improved understanding of the mechanisms that control the rate of cell divisions and expansion may provide novel opportunities to engineer plants that grow more rapidly (Figure 4.7). In addition, advances in characterizing the enzymes and processes responsible for the synthesis and deposition of cell wall polysaccharides may facilitate the development of genetically modified species with increased rates of cellulosic biomass production or the development of plants in which more of the cell wall biomass can be utilized for biofuel production. A major challenge in implementing research in this area is that the long lead-time between initiation of a genetic engineering experi-

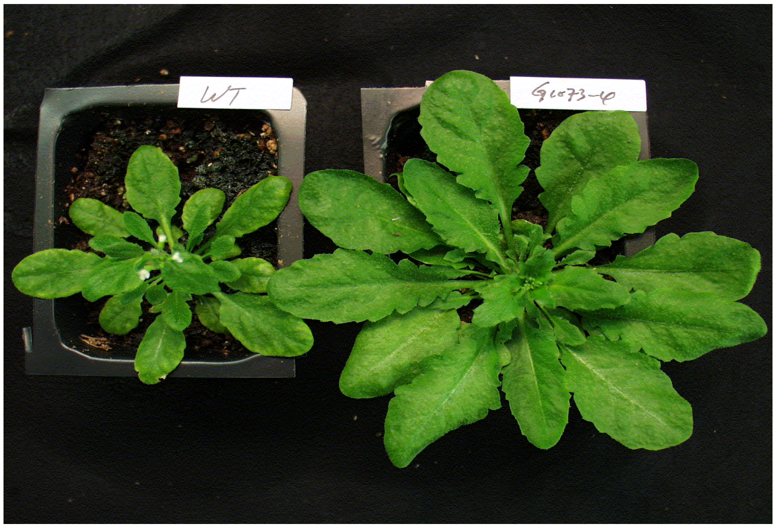


**Figure 4.7. Increased expression of a single transcription factor has a major impact on biomass accumulation. Left: wild type. Right: transgenic.**
*Courtesy of Mendel Biotechnology.*

ment in woody biomass production and the completion of the experiment is on the same time scale as a typical scientific career. Thus, novel career paths for scientists will need to be created before opportunities in this area will be evaluated. One of the most promising approaches today is the hydrolysis of fibrous biomass and subsequent microbial conversion of sugars to ethanol. The proliferation of microbial genome sequence information is a significant new resource in this area. A major opportunity is the development of technologies for conversion of non-cellulosic cell wall polysaccharides, such as pectins, to biofuels.

### *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 retrofit 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.

### Summary

The contribution of renewable energy sources remained relatively small in the year 2000 and present data trends shown in Figures 4.1 and 4.2 are not encouraging. The U.S. Energy Information Administration projects a slight reduction in the fraction of energy supplied from renewable sources between the years 2000-2020. Although absolute usage of renewable energy sources is predicted to increase during this period, total energy consumption is expected to increase at a faster rate, with larger increases in natural gas and oil consumption. Substantial technical breakthroughs are required if the renewable energy technologies are to make a significant contribution to U.S. energy production, particularly for electricity, and the effort to reduce greenhouse gas emissions.

### Resources

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# FUSION ENERGY

A number of nuclear fusion reactions have been considered to provide a future source of energy, but the most feasible in the near term is the fusion of two hydrogen isotopes, deuterium and tritium (DT). The promise of DT fusion energy lies in its potential for an essentially unlimited fuel supply by extracting the required deuterium from terrestrial water supplies while breeding tritium in the reactor itself. The challenge of fusion lies in the need to build and operate one of the most complex engineering structures ever designed which must essentially contain a star in the laboratory. This entails understanding the physics of very high temperature gases (plasma physics) as well as developing the materials and engineering features needed to utilize this energy.

The technical issues that need to be resolved in order to make fusion power a practical reality fall into two broad classes: (1) the creation and maintenance of a burning plasma with an energy density high enough to permit net energy production, and (2) building and maintaining a structure that will permit this energy to be extracted and converted to electricity. There are two alternate schemes under investigation for containing a burning plasma: magnetic and inertial fusion energy (MFE and IFE). In the MFE concept, the plasma is confined and controlled by the interaction between the charged particles that comprise the plasma and powerful magnetic fields. IFE involves the use of either charged particle or laser beams to compress a small fuel pellet to a sufficiently high density for fusion to occur. Most of the pertinent issues related to fusion reactor technology are discussed in documents maintained by the Virtual Laboratory for (fusion) Technology (VLT), at the University of California, San Diego (website, http://vlt.ucsd.edu/).

MFE plasma science and technology has made significant progress in recent years as a series of experimental machines have been built and successfully operated. The larger of these machines include the Joint European Torus (JET) in the United Kingdom, the Tokamak Fusion Test Reactor (TFTR) (recently shutdown) and Doublet-IIID in the U.S., and the JT-60U in Japan. Based on the results obtained from operating these machines, including some experiments that involved burning tritium at JET and TFTR, there is increasing confidence in the plasma fusion community that a burning plasma experiment is feasible, and the international community is moving ahead with plans to build such a machine for this purpose. This machine, the International Thermonuclear Experimental Reactor (ITER), has been the subject of an international design activity since 1988 and a decision is expected this coming year on where to site the construction (see http://www/iter.org/). Candidate sites have been offered in Canada, by the European Union in France and Spain, and in Japan. The U.S. was initially an active partner in the ITER project, but stopped participating in 1999. However, the DOE under the current administration is discussing rejoining the project as the decision on construction approaches.

IFE science and technology has also made significant progress in recent years. Experiments on previous and existing facilities such as the Nova, Omega, and Nike lasers and other foreign facilities have given confidence that larger facilities will produce ignition and energy gain. The IFE program in the Office of Science benefits greatly from a larger inertial fusion program administered by the National Nuclear Security Administration (NNSA). In particular, NNSA is currently building a facility, the National Ignition Facility (NIF) to study burning IFE plasmas. A similar facility, the Laser Mega-Joule (LMJ), is under construction in France.

The issue of the next step experimental machine for investigating burning plasmas was the topic of a two-week meeting in Snowmass, CO in July 2002. This meeting involved more than 280 U.S. and foreign scientists in what was called the *2002 Fusion Summer Study.* Objectives of the *Fusion Summer Study* were:

- to review scientific issues in burning plasmas for MFE and IFE confinement,
- to provide a forum for critical discussion and review of proposed MFE burning plasma experiments and assess the scientific and technological research opportunities and prospective benefits of these approaches to the study of burning plasmas, and
- to provide a forum for the IFE community to present plans for prospective integrated research facilities, assess present status of the technical base for each, and identify a timetable and technical progress necessary for each to proceed.

The meeting summary (available at http://web.gat.com/snowmass/) strongly endorses building such an MFE burning plasma experiment, and identifies the issues and benefits associated with ITER and two alternate machines called FIRE (Fusion Ignition Research Experiment) and IGNITOR. As noted above, the burning plasma experiment for IFE conditions (http://www.llnl.gov/nif/) is currently under construction.

Although the successful control and maintenance of a burning plasma is not assured, increasing attention is now being placed on developing the materials and technology to use the DT fusion source to produce power. These latter issues are a focus of the material on the VLT website mentioned above. The high-energy neutrons created in the plasma will produce radiation damage problems in the structural materials that are similar to, but more severe than, those experienced by in-core components in fission reactors. In fact, materials development research in the fusion reactor program has in many cases paralleled that of advanced fission reactor programs. The major differences between the DT fusion and fission environments are the neutron energy spectrum. DT fusion neutrons are all born at 14.1 MeV while the fission source exhibits a spectrum with a peak near 2 MeV. The neutron spectra in both cases cover a wide range of energy as a consequence of scattering reactions. However, the presence of higher energy fusion neutrons has two major impacts: (a) higher energy primary atomic recoils and (b) high nuclear transmutation production since many such reactions have energy thresholds well above 2 MeV. In particular, the rate of helium and hydrogen generation by $(n,\alpha)$ and (n,p) reactions is on the order of 10 to 100 times higher in the DT fusion case. The required damage levels for components in the highest flux positions in DT fusion reactors are also greater than that in fission reactors.

The lack of an intense 14 MeV neutron source requires that the fusion program obtain radiation effects data primarily from irradiation experiments carried out in fission reactors. As a result, much of the previous experimental and modeling work in the fusion materials program has been aimed at determining the impact of the higher energy DT neutrons. Modern computational simulations support the view that the net effect of spectral differences between fission and fusion may be rather small. This conclusion is also supported by some experimental evaluations that indicates the use of a common correlation parameter (atomic displacements per atom, dpa) seems to account for spectral effects arising from differences in primary displacement damage production. However, the computational results provide information on the radiation damage source term only for times up to ~100 picoseconds, and do not account for the differences that may arise from transmutation products such as helium and hydrogen. Thus, additional research is required to confidently extrapolate the fission reactor data to DT fusion conditions. A good summary of the fusion materials research issues and opportunities is referenced below [Stoller et al. 1999].

Because of the system complexities, the need for materials research extends beyond radiation effects in structural materials. For example, plasma diagnostic systems require materials whose electrical performance may be degraded by irradiation, and the performance of optical materials used as windows and mirrors in both MFE and IFE systems may also be radiation sensitive. Superconducting materials are another example. Low cost, low degradation under irradiation and high temperature are desired properties. In addition, tritium must be bred by transmutation of lithium in a blanket region near the structural first wall. Both solid (ceramic) and liquid (liquid metals and molten salts) breeding materials have been investigated. Relevant research issues include the development and use of coatings to prevent the buildup of tritium in the blanket structure, corrosion issues, and the technology to extract tritium from the breeding medium.

If the technical issues with developing fusion energy are solved, further improvements may be required for this technology to be economically competitive. For example, a recent study [Delene et al. 2001] compared the projected cost (in the year 2050) of electricity from fusion with several other options, including coal, natural gas, nuclear fission, and wind. Two tokomak fusion designs included were ARIES-RS and ARIES-ST [Bathke 1997]. The other systems evaluated were generally advanced variants of current technologies: pulverized coal with flue gas desulfurization, pressurized fluidized-bed coal combustion, combined cycle coal-gasification, combined cycle natural-gas fired turbine, advanced light water fission reactor, advanced liquid metal fission reactor, and a wind turbine. The estimated baseline levelized cost of electricity from the fusion designs was 2.5 x $10^{-2}$ cents/MJ to 2.7 x $10^{-2}$ cents/MJ (91 and 97 mils/kWh) for the two fusion designs. This compares to a range of 8.3 x $10^{-3}$ cents/MJ to 1.9 x $10^{-2}$ cents/MJ (30 to 67 mils/kWh) for the other technologies. A range of assumptions was investigated in this study, but electricity from the tokomak fusion designs was consistently higher.

In summary, substantial levels of basic and applied research and development are required before the promise of fusion can be realized. The results of current plasma physics experiments increase confidence in the scientific feasibility of maintaining a burning plasma, and progress has been made in understanding the engineering issues associated with extracting and using the fusion energy produced. However, fundamental research related to materials performance, research on issues related to tritium breeding and extraction, and additional system design and integration studies are needed. Finally, technical feasibility does not ensure the economic viability of fusion. The perceived environmental advantages may offset some economic penalty, but history suggests that price will remain a strong selector in the energy marketplace.

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## Other Resources

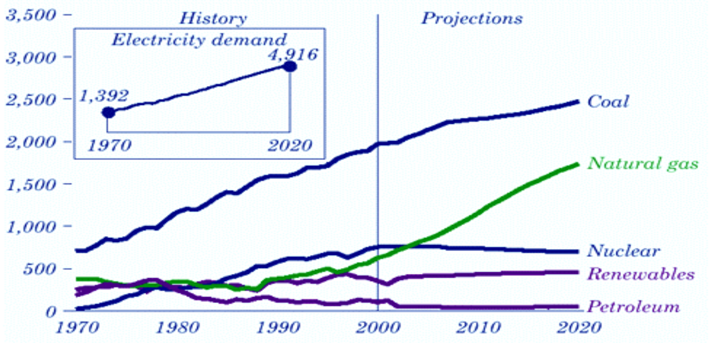
Inertial Fusion Energy Experiment. (http://www.llnl.gov/nif/)

ITER development. (http://www/iter.org/)

Virtual Laboratory for Technology (VLT), at the University of California, San Diego. (http://vlt.ucsd.edu/)

# DISTRIBUTED ENERGY, FUEL CELLS, AND HYDROGEN

It is projected that by the year 2020 an estimated 6 trillion MJ (1.7 trillion kWh) of additional electric capacity, corresponding to about 200 generating plants with a 1 GW power capacity, will be required in the United States to meet new demand and replace lost capacity from retired power plants. (Figure 6-1.) This is almost twice the growth rate of the last 20 years. Estimates for the worldwide consumption of electricity show an increase from 12 billion MJ/s used in 1996 to possibly 22 billion MJ/s by 2020. Developing countries, where an estimated two billion people live in rural areas with no access to power grids, are projected to account for most of this increase. Distributed generation technologies are expected to capture a considerable part of this market with an estimated increased capacity of over 20,000 MJ/s (20 GW) per year over the next decade.



History: Energy Information Administration (EIA), Form EIA-860B, "Annual Electric Generator Report— Nonutility"; EIA, *Annual Energy Review 2000*, DOE/EIA- 0384(2000) (Washington, DC, August 2001); and Edison Electric Institute.

**Figure 6-1. Electricity generation by fuel for the year 1970-2020 (billion kWh).**

The term "distributed power generation" refers to placing small power generation units [typically less than 30 MJ/s (30 MW)] at or near customer sites to relieve burdens on existing transmission and distribution systems during peak use times or to provide standby power for customers that, either for health and safety or economic reasons (such as hospitals and some industries), cannot tolerate an interruption of service. Distributed power generation systems can be used in stand-alone situations, such as remote locations where no power grid exists or in industries where tight control of the quality and level of power is required. Heat generated by the power system can also be used in cogeneration applications, such as providing heating and cooling for buildings. Power sources for such applications need to be cost effective, dependable, efficient, relatively mobile, and have a minimal environmental impact. Gas turbines and reciprocating engines are already being used for distributed power generation and their efficiency may be improved further by continued materials and systems development. Emerging technologies, including microturbines and fuel cells, offer promise for providing additional options that could meet the efficiency and environmental criteria.

Critical issues in the envisioned technologies are the availability and nature of the fuel, its production, storage, transport, and efficient conversion into electrical energy. Fuel types may be divided broadly into carbon-free fuel (i.e., hydrogen) and carbon-containing fuels such as reformer gas or hydrocarbons.

**Hydrogen as a fuel** [adapted in part from IWG 2000]

It is recognized and accepted that once delivered to the energy conversion device, high purity hydrogen is the ideal fuel. Despite its abundance in nature, hydrogen is not a primary energy source, and must be produced from a primary energy source such as fossil hydrocarbons or coal, nuclear fission or fusion, hydroelectric, or renewable technologies. Depending on the source, its production may or may not involve $CO_2$ emissions. When hydrogen is produced from carbon-containing primary energy sources, e.g. by steam reforming of hydrocarbons, $CO_2$ appears as a by-product. Subsequent sequestration could result in low emissions of $CO_2$, compared to combustion, depending on the efficiency of the hydrogen production process. Nuclear power could be used to generate hydrogen, either through electrolysis of water or through thermochemical processes involving high temperature reactors. Hydroelectric power is well suited for the utilization of the off-peak plant capacity. 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:

- hydrogen by electrolysis of water, with electricity produced by nuclear, hydroelectric, solar or wind power plants;
- photoelectrochemical- and photobiological-based processes for producing hydrogen from water; and
- thermochemical conversion using advanced high-temperature nuclear or solar reactors, coupled to chemical reaction cycles.

It is important to consider the complete fuel cycle (i.e., the "well-to-wheel" efficiency [SNRA 2001, GM 2001], in the generation and use of hydrogen from fossil sources) when evaluating the overall environmental and fossil fuel savings for electrochemical energy conversion and when making comparisons with advanced combustion engines. The electricity consumed in the hydrogen generation by electrolysis could alternatively be directly delivered to the grid. Hydrogen as a fuel then retains merit in mobile or in remote applications, where a grid is not present, or where pollution reduction is an overriding concern. Furthermore, hydrogen has been proposed as a method of storing energy of intrinsically intermittent electrical power sources, such as wind and solar power.

Hydrogen is produced today in large quantities, primarily for use in the chemical and oil refining industries. Modest amounts of hydrogen are distributed by pipeline or truck to industrial users. Hydrogen production, storage and distribution methods are commercially available, but dramatic improvement, particularly of existing storage technologies for transportation, is needed if hydrogen is to become a major energy carrier in the future. Advanced storage concepts include complex hydrides, e.g., alanates [Zaluska et al. 2000], carbon adsorption and carbon nano-tube encapsulation. Many of the more promising concepts are still in the basic research stage, but are of questionable economic value, or are controversial [Ye et al. 2002, Züttel 2002]. Distribution systems would also have to be deployed that are capable of containing and pumping the low molecular weight fuel, utilizing materials that resist hydrogen embrittlement.

Key criteria for successful use of hydrogen in the transportation market is the energy density of the storage system, as compared to other fuels. Table 6-1 [Berry and Aceves 1998, Pettersson and Hjortsberg 1999]

**Table 6.1. Estimated Storage Performance of Hydrocarbon in Tanks Designed for 640-km Range in a 34-km/l Gasoline Equivalent Car**

| Vessel type | Volume (l) | Weight (kg) | $H_2$ (kg) | E/V (MJ/l) | E/m (MJ/kg) | Reference |
|---|---|---|---|---|---|---|
| 344 bar pressure $H_2$ | 237 | 37 | 5 | 2.5 | 22 | Berry 1998 |
| Liquid $H_2$ | 135 | 31 | 5 | 4.4 | 19 | Berry 1998 |
| 344 bar cryogenic pressure $H_2$ | 126 | 66 | 5.17 | 4.9 | 9.4 | Berry 1998 |
| 600 bar carbon/polymer $H_2$ | -- | -- | -- | 3.5 | 7.5 | Dillon 1997 |
| "Metal hydride" $H_2$ | 66 | 184 | 5.7 | 10 | 3.7 | Klos 1998 |
| Methanol | 62 | 46 | -- | 11 | 15 | Klos 1998 |
| Gasoline | 39 | 29 | -- | 17 | 23 | Klos 1998 |
| Compressed natural gas | -- | -- | -- | 6-10 | 13-20 | T-Raissi 1996 |

*Source: Pettersson and Hjortsberg 1999*

shows the projected volume and weight needed for a typical automobile using different hydrogen vessels and other fuels. Gasoline has the best performance in mobile applications. As yet, any of the known hydrogen storage methods do not compare, being either too heavy or to voluminous, or both.

In principle, the introduction of a hydrogen economy might proceed by a gradual transition from exclusive fossil fuel use to significant inclusion of non-carbon primary energy sources, reducing $CO_2$ and other emissions and full dependence on fossil fuels. At full market penetration, all conventional use of fossil fuels would be replaced by hydrogen derived from renewable, nuclear, or carbon-sequestered fossil-fuel sources.

Hydrogen as a fuel has been researched for nearly 25 years and is currently strongly promoted [Shell 2002] for mobile applications. Significant technical and economic uncertainties remain as obstacles to its broad deployment in the U.S. economy. At a minimum, before hydrogen can achieve a premiere status in the energy economy, dramatic advances will be required in hydrogen storage and carbon-free production technologies, while focused research programs aimed at innovation in this area should be formulated in realistic economic contexts.

### Heat Engines

Heat engines, including various reciprocating types, gas turbines, and microturbines constitute a well-known and well-developed technology. They are presently the lowest-cost distributed generation technology. Since heat engines operate on Carnot cycle or other heat/pressure cycles, higher operating temperatures as well as heat recuperation can improve their overall efficiencies. The development of novel materials or coatings that can withstand combustion temperatures significantly above the present limits remains an area where basic materials research and development can produce significant benefit.

Heat engines are quite adaptable to alternative fuels such as landfill gas, propane, and gases derived from gasification of coal, biomass, and various types of waste. They can be used in a variety of applications because of their small size, low capital costs, easy start-up, reliable thermal output, good load-following characteristics, and heat recovery potential. In addition, developments over the past several years in exhaust catalysts and combustion design and control have resulted in significantly reduced pollutant emissions. They are suitable for many distributed power generation applications, and constitute a large portion of the combined heat and power (or cogeneration) market that currently accounts for about 7% of the electricity produced in the U.S. Typical installed costs are $250-450 per kJ/s and, in large size, can operate at a maximum efficiency of approximately 50% thermal.

Although heat engines have been characterized as being maintenance intensive, they have been produced for well over a hundred years, and therefore already have the support of a well-established base of sales and service outlets. Their ease of use and ready availability has, in fact, at times discouraged the search for alternative technology. The major drawbacks of combustion engines are their relatively limited lifetime (typically about 5000 hrs for reciprocating engines, e.g.), noise, and various pollutants, which need to be improved significantly for extended, continuous distributed service.

### Fuel Cells

A fuel cell produces electric energy through an electrochemical reaction that combines a hydrogen or hydrocarbon fuel and air or oxygen to produce water, carbon dioxide (for hydrocarbon fuel or hydrogen derived from a carbon-containing primary fuel), and heat. Because they are not Carnot-cycle limited, fuel cells can be highly efficient, clean, quiet, and reliable. The fuel cell consists of an anode into which the hydrogen or hydrocarbon fuel is fed, a cathode through which the oxygen (or air) enters, and an electrolyte that separates the two electrodes. Polymeric electrolytes for the PEM fuel cells transport protons in association with several water molecules. Solid oxide electrolytes for the SOFC fuel cells exclusively transport oxygen ions. While the ions pass through the electrolyte, the electrons must take a separate path around the electrolyte, creating a current that can be utilized. The PEM fuel cells, operating around $100^oC$ are strictly hydrogen cells, where the hydrogen has to be supplied as such, or produced by reformers. They are presently intensely developed [Ballard 2002]. The solid oxide fuel cells, operating at temperatures up to $1000^oC$ can use not only hydrogen but also fossil fuels directly. This is a substantial advantage in a distributed generation scenario when a hydrogen infrastructure is not yet developed. In addition to water and heat, the fuel cell reactions produce carbon dioxide, not or minimally diluted by nitrogen – in contrast to combustion engines – that can be captured for recycling or sequestration.

There are five major types of fuel cells, each designated by the type of electrolyte used: alkaline (AFC), phosphoric acid (PAFC), polymer or proton-exchange membrane (PEMFC), molten carbonate (MCFC), and solid oxide (SOFC). Each of these are slightly different in the materials used for the different parts of the cell, the temperatures at which they will operate, and the source and type of fuel that they will accept. The dominant variants presently are the PEMFC and the SOFC, based on known cost and performance ceilings in the other fuel cell types. For the PEMFC a system that includes a “fuel reformer” can generate hydrogen from any hydrocarbon fuel, including natural gas, ethanol, methanol, and gasoline. Cells can be constructed to serve virtually any power requirement, from mJ/sec to MJ/sec, with little variation in efficiency.

Many potential applications for fuel cells are envisioned. More than 200 PAFCs have already been installed all over the world at stationary sites such as hospitals, nursing homes, hotels, office buildings, schools, airport terminals, etc., where they provide primary power or backup at a cost savings of 20-40% over conventional energy service. In addition, several are being used at landfills and wastewater treatment plants in this country where they use the methane gas produced at the site to generate power. Unfortunately, the PAFCs cost about $3000 to $5000/kW, and 10-15 years of manufacturing development have failed to impact this cost.

Since fuel cells produce little or no noise, have low emissions, and can operate directly or indirectly on propane, natural gas, or other fossil fuels, as well as locally derived hydrogen, they are ideally suited for distributed power generation applications. They can not only produce the needed electricity but also use heat from the fuel cell to provide hot water or space heating. The low-grade heat (~80$^o$C) from the current PEM fuel cell technology may also be used to provide air conditioning via a desiccant cooling cycle. The high temperature of the SOFCs also allows the exhaust gas to drive a turbine, in contrast to the PEMFC. Potential transportation applications include off-road utility vehicles, buses, trains, and even boats. As part of the national FreedomCAR Program, all the major automotive manufacturers (including Ford, General Motors, Honda, and Toyota) have a PEM fuel cell powered vehicle either in development or testing. SOFCs, under a strong development technology program through the National Energy Technology Laboratory (NETL) [NETL 2002], can offer higher overall efficiencies than PEM cells and, while mobile applications are also possible, they are envisioned chiefly for stationary distributed generation from a few kilowatts up to the megawatt range [NETL 2002].

In spite of the attractive system efficiencies, environmental benefits, and energy security that fuel cells in a distributed power generating economy could provide, they have yet to capture a significant portion of the energy market. A critical issue in this delay is the cost of the fuel cell systems. Presently, SOFCs and PEMFCs that have demonstrated extended performance (i.e., in excess of 10,000 hrs of continuous operation) are excessively costly. The current capital costs of such fuel cells ($3000-10,000 per kJ/s) must be reduced considerably before they can become economically competitive with existing energy technologies. This situation is not a consequence of engineering or marketing inadequacy. Rather, the requirement of significant cost reduction has imposed the development of fuel cell systems that use inherently low-cost materials and processing techniques. The development has been hampered by an insufficient science base that can accurately predict materials properties and compatibilities in fuel cell environments.

### Research Needs

There are many research opportunities in the development of novel fuel sources, efficient fuel cells, engines and turbines for distributed energy applications. Fundamental research is needed to improve the understanding of the chemical, physical, and mechanical properties of materials used in fuel cells, and in hydrogen generation, transportation, and storage. Advancements in these areas could lead to new designs and possibilities for using lower-cost and easier-to-manufacture materials. Significant advances are needed for stack materials, oxygen cathodes, and membranes, including metals, ceramics, and polymers. These could lead to the development of durable PEMFCs that operate at higher temperatures, and SOFCs that operate at lower temperatures.

Hydrogen direct combustion devices can benefit from continued fundamental research. Needed are engine and turbine materials that resist corrosion and operate efficiently and reliably at higher temperatures, more durable and lower cost sensors and instrumentation, and better performing hydrogen-natural gas fuel blends.

A breakthrough in hydrogen storage technologies would profoundly impact the feasibility of the hydrogen economy.

The areas where innovative basic materials research, sensitive to economic factors, can be formulated to lead most effectively to energy improved technology may be broadly listed as:

- materials physics and chemistry of functional surfaces and interfaces, including structural, electrochemical, catalytic, and corrosion protection functions;
- predictive theories of composition and structure of ceramic and polymeric materials for high oxygen ion or proton conduction, constrained by cost;
- materials physics and chemistry of mixed electron/ion conductors;
- materials physics and chemistry of ultrahigh capacity, lightweight hydrogen storage materials;
- materials physics and chemistry of novel hydrogen production technologies; and
- limits of strength of materials for hydrogen pressure vessels, both theoretical and after processing.

## Summary

Distributed power generation is still in its infancy. For advanced distributed power generation systems to become a reality for general power production applications, significant manufacturing cost reductions and further improvements in materials performance are needed in all of the systems listed above. These improvements will depend principally on innovative development of high-performance and yet low-cost materials, as well as on identification of cost-effective manufacturing techniques. While the near term options for distributed generation applications include reciprocating engines and gas turbines, in a distributed power generation economy operating on hydrogen or carbon containing fuels, fuel cells in combination with microturbines can ultimately provide the needed environmental benefits, reduce the critical dependence on fossil fuel, and provide the necessary energy security.

The realization of these materials-limited advanced technologies depends critically on the information that basic materials sciences studies need to provide.

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# TRANSPORTATION ENERGY CONSUMPTION

The U.S. transportation sector includes highway, air, rail, shipping, pipeline, and off-road transport, as well as other categories such as recreational boats and military fuel consumption. In the year 2000, the sector consumed about 28.8 EJ (27.3 Quads) of primary energy, which translates into 28% of total U.S. energy consumption. The sector is also the nation's primary oil consumer at 27 EJ (13.3 million barrels per day [mbd]) in the year 1999, or about 67% of total U.S. consumption. Transportation is almost exclusively dependent on petroleum; over 97% of all energy used in the sector comes from oil. Transportation is responsible for almost one-third of U.S. carbon emissions, substantial amounts of most air pollutants, and two-thirds of U.S. oil consumption (Table 7.1). In the same year, the sector emitted 502 million metric tons (MtC) of carbon, or 32% of the U.S. total carbon emissions. In the face of strong continuing demand for transportation services, slow turnover of fleets, gasoline's dominance of light-duty vehicle fueling infrastructure, and low energy prices that provide only modest incentives for improved efficiency, U.S. transportation energy consumption and greenhouse gas (GHG) emissions are expected to grow robustly over the next few decades.

**Table 7.1. Contribution of the Transportation Sector to National Issues and Problems for the Year 1999**

| National Issue | Amount | % of U.S. Amount |
|---|---|---|
| Climate Change – Carbon Emissions | 502.0 MtC | 33 |
| Air Pollution – CO | 84.6 Mt | 80 |
| Air Pollution – NOx | 11.6 Mt | 54 |
| Air Pollution – VOC | 7.7 Mt | 44 |
| Air Pollution – PM-10 | 0.5 Mt | 3 |
| Air Pollution – PM-2.5 | 0.5 Mt | 7 |
| Air Pollution – $SO_2$ | 0.7 Mt | 4 |
| Oil Dependence – Oil Use | 27.1 EJ (25.65 Quads) | 67 |

*Source: EIA 2001 ($CO_2$ and oil dependence), EPA 2002 (other air emissions)*

## Overview of the Sector

Highway travel dominates the U.S. transportation sector, consuming 75% of the total energy used by the sector. In the highway sector, light-duty passenger travel is dominant, accounting for 74% of highway energy consumption, and 56% of *total* transportation energy consumption. Figure 7.1 shows the modal breakout of energy consumption. The characteristics of the various fleets in the sector and recent trends in energy use provide important clues to likely future energy use in the sector and the potential for reducing GHG emissions. Some critical points about the transportation sector include:

- New light-duty passenger vehicles have been adopting fuel-efficient technologies over the past decade and a half, but consumer shifts to increasing vehicle size, weight and especially performance have nullified potential fuel economy gains from these technologies.

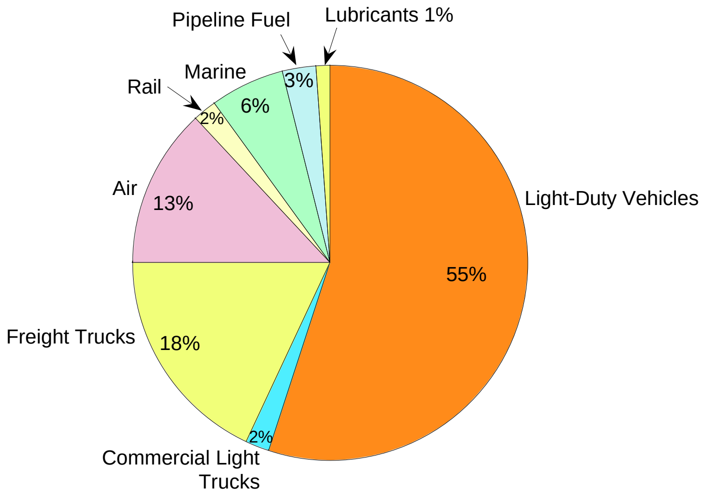

**Figure 7.1. Year 2000 Transportation Energy Use by Mode (27.3 Quads/28.8 EJ)**
*Source: EIA 2001*

- Important new technologies have entered the fleet, including port fuel injection, four- valves/cylinder engines, variable valve control, structural redesign for improved safety and reduced weight, growing use of high-strength steel and steel substitutes such as aluminum and plastics, and low-rolling resistance tires.

- Counteracting trends indicate the consumer shift to more inefficient vehicles, including the growing sales share of light-duty trucks (including Sport Utility Vehicles), which now comprise 46% of light-duty vehicle sales, up from 17% in the year 1980; horsepower to weight ratios 45% higher than in year 1980, an increase in weight over year 1980 vehicles [Heavenrich and Hellman 1999]; greater shares of four-wheel drive installed on 47% of year 1999 model light trucks, and other luxury features.

- As a result of a decade of low gasoline prices, consumer surveys show that today's auto purchasers generally are not interested in fuel economy.

- The "potential technology" portfolio for automobiles has been enhanced substantially by government/industry joint research and development programs [NRC 1999]. The impacts of this research are both direct and indirect, including stimulation of competitive developments in Europe and Japan.

- Freight transport now consumes about 30% of U.S. transportation energy, with freight energy use, but *not* gross ton-miles, dominated by heavy truck carriage (over 50% of energy use, about one-quarter of ton-miles) [Davis 1998, table 2.13], the most energy-intensive mode aside from air freight. Air freight and freight truck energy use are the most rapidly growing freight modes because of the U.S. economy's shift towards higher value (and more time-sensitive) goods. A countervailing trend is greater use of multi-modal shipments, advanced by the rationalization of U.S. freight railroads and the benefits of improved computerized information systems.

## Examples of Promising Technologies

The transportation sector has a wide variety of available and emerging technologies that offer the potential to reduce significantly the energy use and GHG emissions associated with transportation services.

**Cellulosic Ethanol.** About one billion gallons of ethanol produced from corn are currently used annually in U.S. transportation markets as a blend stock for gasoline [Davis 1998]. Although the efficiencies and fuel choices used over the fuel cycle in producing ethanol vary widely (e.g., fuel choices for powering the distillery can be corn stover, natural gas, or coal), recent studies show that the use of ethanol provides a moderate GHG advantage of about 20% over gasoline. Processes to produce ethanol from cellulose – from woody biomass or municipal wastes – for use as a gasoline blending agent or neat fuel offer reduction of greenhouse gases by about 80% compared to gasoline [Wang et al. 1999]. Land requirements could ultimately limit cellulosic ethanol production. About 15 billion gallons of ethanol (1.2 EJ/1.3 Quads) could be produced annually by converting municipal and agricultural wastes with minimal land requirements [Lynd 1997]. If about 35 million of the roughly 60 million acres idled by Federal programs were used for energy crops, about 25-32 billion gallons, or about 2.8-3.8 EJ (3-4 Quads) of ethanol could be produced annually (assumptions: 8.4 dry tons/acre/year crop productivity, 107.7 gallons of ethanol/ton yield) [Lynd 1997]. If only 10 billion gallons of ethanol were produced annually, this would leave 200 million dry tons of biomass for other uses, such as biomass power.

**Hybrid Electric Drive Trains.** A hybrid electric drive train combines an internal combustion engine or other fueled power source with an electric drive train including an electric motor and battery (or other electrical power source, e.g., an ultra capacitor). Potential efficiency gains involve recapture of braking energy (with motor used as generator, captured electricity stored in the battery); potential to downsize the engine, using the motor/battery as power booster; potential to avoid idling losses by turning off the engine or storing unused power in the battery; and increasing average engine efficiency by using the storage and power capacity of the electric drive train to keep the engine operating away from low efficiency modes.

**Lower Weight Structural Materials.** The use of alternative materials to reduce weight has been historically constrained by cost considerations, manufacturing process technology barriers, and the difficulty of these materials in meeting automotive requirements for criteria such as surface finish quality, predictable behavior during crash tests, or repairability. The last few years have seen significant developments in overcoming such barriers through design changes such as a space frame-based structure; advanced new manufacturing technology for plastics, composites, ceramics, and aluminum; and improved modeling techniques for evaluating deformability and crash properties.

**Direct Injection Gasoline and Diesel Engines.** Direct-injection lean-burn gasoline engines have already been introduced in Japan and Europe, but have been restricted here by a combination of tight emission standards and high sulfur content in gasoline. Catalytic converters capable of reducing $NO_x$ emissions from lean-burn engines are very sensitive to fuel sulfur content, and no simple remedy has been found. Direct-injection diesel engines have long been available for heavy trucks, but recently have become suitable for automobiles and light trucks, with reductions in noise and emission problems. These new engines are about 25-30% more fuel efficient, on a per gallon basis, than conventional gasoline engines (roughly half of the gain from higher engine energy efficiency and half from the higher energy density of diesel fuel). Diesel engines are about 15% more efficient on the basis of carbon emissions over the fuel cycle. Federal Tier 2 emission regulations require light-duty diesel vehicles to attain the same (low) $NO_x$ levels as gasoline vehicles, as well as stringent particulate levels. These standards will require new active aftertreatment that may reduce the fuel economy benefit significantly. Federal emission standards for heavy-duty engines that become effective in the year 2007 are similarly challenging. These new federal standards present a challenge to diesel's viability. Federal rules will require diesel fuel to be less than 15 ppm sulfur after the year 2006. Further improvements in diesel technology offer substantial promise in heavy-duty applications, especially for heavy trucks but also include marine and rail applications.

**Fuel Cells.** Fuel cells have been called the "Holy Grail" of clean powertrain technology, with promise of zero or near-zero criteria pollutant emissions and very high efficiency. The recent optimism has been driven by strong advances in technology performance, including rapid increases in specific power that now allow a fuel cell powertrain to fit into the same space as a conventional engine without sacrificing performance [Griffiths 1999]. However, fuel cells remain extremely expensive, and long-term costs are by no means clear. Further, important technical roadblocks remain, such as operation in extreme weather conditions. Another central issue is fuel choice. Fuel cells need hydrogen, either carried on board or produced by reforming methanol or gasoline. Carrying hydrogen may yield the cheapest and most fuel-efficient vehicle, but no hydrogen distribution and refueling infrastructure exists. A gasoline vehicle overcomes the infrastructure problem but is the most expensive and least efficient vehicle. Developing an adequate gasoline processor remains a critical task, with significant improvements required in processor weight and size, cost, response time, efficiency, and output of carbon monoxide, which can poison the fuel cell stack [NRC 1999]. While methanol could be an alternative, it is water soluble and toxic to humans with invisible flame that also requires a substantially improved fuel processor and, as yet, has no real infrastructure for distribution. Additionally, hydrogen and liquid fuel versions are likely to be more expensive initially than an equivalent conventional automobile. Hydrogen is an energy "carrier", not an energy feedstock, and must be produced from other energy resources. Hydrogen production from fossil feedstocks would require carbon sequestration to avoid net GHG emissions. Further, the cost of producing hydrogen must be weighed against any improvement in efficiency.

**Aircraft Technology.** Several major technologies offer the opportunity to improve the energy efficiency of commercial aircraft by 40% or more. The Aeronautics and Space Engineering Board of the NRC [NRC 1992] concluded that it was feasible to reduce fuel burn per seat mile for new commercial aircraft by 40% by about the year 2020. Of the 40% reduction, 25% was expected to come from improved engine performance, and 15% from improved aerodynamics and weight. A reasonable preliminary goal for reductions in $NO_x$ emissions was estimated to be 20-30%.

## Potential Research Directions

In the long term, additional advances hold the promise of large reductions in energy use, GHG emissions, and air pollution from the transportation sector. Opportunities lie in 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 may create new opportunities to increase system-wide efficiency and substitute communication for transportation to enhance economic well being and the overall quality of life. Promising areas for continuing research include:

**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 internal combustion engine (ICE) with an electrical power source (battery and electric motor). Fuel-cell-powered electric vehicles (FCEVs) have been demonstrated with and without batteries for onboard storage of electrical energy. 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). On-board hydrogen and biofuels offer the options for zero net GHG emissions from personal transportation, should that be required for stabilization of atmospheric carbon. While HEVs are already on the market, their incremental costs are too high to enable large-scale market penetration.

HEVs, EVs, and FCEVs 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. FCEVs will also require cost reductions (by nearly an order of magnitude) as well as improvements in hydrogen storage and reliability. Carbon savings from EVs depend directly on the primary energy sources used to generate the electricity that charges the batteries. Potential advances in electricity generation technology could make EVs very-low-carbon vehicles. However, the choice of fuels used by electrical utilities 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 improved further to 55% by use of technologies such 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 10-20%, on a full fuel-cycle basis, over conventional gasoline or diesel fuel. Far more promising in reducing GHG are biofuels, such as biodiesel produced from soy or rapeseed oils or ethanol or methanol produced from cellulosic feedstocks. 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. 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 (<500 miles) intercity travel, at the same time relieving both air traffic and highway congestion. Such benefits will depend, crucially, on the level of train ridership. 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. These approaches 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 will reduce carbon emissions and petroleum use, which is critical to retaining competitiveness in the U.S. aircraft industry. 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. 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.

### Summary

Energy use and carbon emissions from transportation have grown steadily and appear likely to continue to grow without new policies or sharp changes in fuel prices and availability. The direct physical causes of this growth have been:

- Travel demand has continued to grow strongly as incomes and population have risen; for example, personal vehicle miles traveled (vmt) grew by 2.8% per year during the years 1974-1995.
- Light-duty fuel economy has stagnated over the past decade.
- Vehicle technology has changed over time, but much of the technology has been used for purposes other than higher efficiency.

Several factors will strongly influence future levels of transportation energy use and GHG emissions. On the favorable side, a variety of technology options currently are available to reduce energy use and emissions, and a substantial portfolio of advanced technologies is under development. Obtaining large emissions reductions will require counteracting a number of factors, including:

- inexpensive fuel and consequent disinterest in fuel economy among light-duty vehicle purchasers;
- fuel efficiency trade-offs with vehicle characteristics that *are* of interest to vehicle purchasers such as acceleration performance, vehicle size, and consumer features such as four-wheel drive, etc.;
- time required for redesign, retooling, and fleet turnover because the full benefits of new technologies take years to develop;
- high costs and/or important technological and market risks associated with some of the most promising fuel economy technologies; and
- uncompetitive features of alternative modes of personal transport (travel time, security, comfort, etc.)

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# RESIDENTIAL, COMMERCIAL, AND INDUSTRIAL ENERGY CONSUMPTION

In addressing the issues regarding the residential, commercial and industrial energy consumption, the research focus should be established with an eye on the future energy landscape and requirements, and not be limited by the current prevailing technologies and demand patterns. In looking forward, Society will be confronted with significant new challenges in the next 50 years. The availability of a rich, high quality, scientific research base carried to the pre-competitive level will be the best strategy for coping with future energy requirements. A new way of thinking by policy makers and scientific program managers will be needed to establish a viable long-range research agenda. The activities supported will not only have to deal with their own intrinsic dimensions but with the impact of extrinsic advances of science and technology more generally in an increasingly integrated manner than in the past. The development of applications and hand off to industry will require feasibility and cost-effectiveness demonstrations, following the basic research phase.

The objective of the workshop is to come up with several aggressive and imaginative research directions that will have the potential for a significant impact on reducing residential, commercial and industrial energy consumption with commentary on the methodology used in the identification of these research directions. Several tentative suggestions are listed in this background paper for consideration as possible new research directions. The focus of the workshop is to seriously develop bold, new research directions through briefings, discussions and brainstorming.

For ease of analysis, the energy consumption of the residential, commercial and industrial sector has been divided into two subgroups. The first subgroup combines the commercial and residential energy use in the buildings sector, while the second subgroup summarizes the energy use for the diverse industrial sector. Much of this information was taken from the report, *Scenarios for a Clean Energy Futures* [Interlaboratory Working Group 2000].

## Buildings (Commercial and Residential) Sector

**Overview of Sector:** Energy is used in buildings to provide a variety of services such as space heating, space cooling, water heating, lighting, refrigeration, and electricity for electronics and other equipment. In the U.S., building energy consumption accounts for a little more than one-third of total primary energy consumption and related greenhouse gas emissions. The cost of delivering all energy services in buildings (such as cold food, lighted offices, and warm houses) was about $234 billion in the year 2000 [U.S. DOE 2002]. About 69% of building sector energy use is electricity, and this sector uses about 68% of all electricity generated nationally. Natural gas accounts for 23% of total energy in this sector, and electricity and natural gas account together for about 92% of building sector primary energy use. Oil consumption is only 2% of the total, although it is a significant heating fuel in the Northeast.

**Buildings Sector Primary Energy Use in Year 2000:** Figure 8-1 and Figure 8-2 show the percentage breakdown of primary energy use by end-use in residential and commercial buildings, respectively. The breakdown of carbon emissions by end-use tracks the primary energy breakdown closely. Space heating is by far the largest identified end-use in the residential sector, accounting for just about one third of the primary energy. Water heating is next, followed by space cooling, refrigerator/freezers and lighting. The adjustment (9%) is for miscellaneous uses not identified and to reconcile totals to the EIA (Energy Infor-

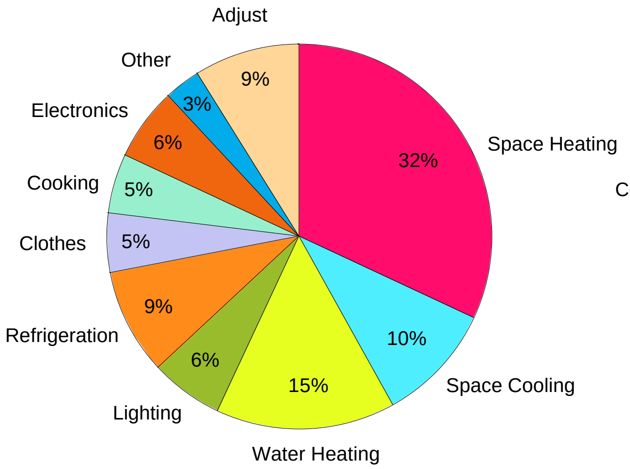

**Figure 8-1. Primary energy consumption in residential buildings by end use for year 2000. Total primary energy use = 21.0 EJ (19.9 Quads).** *Source: U.S. DOE 2002*

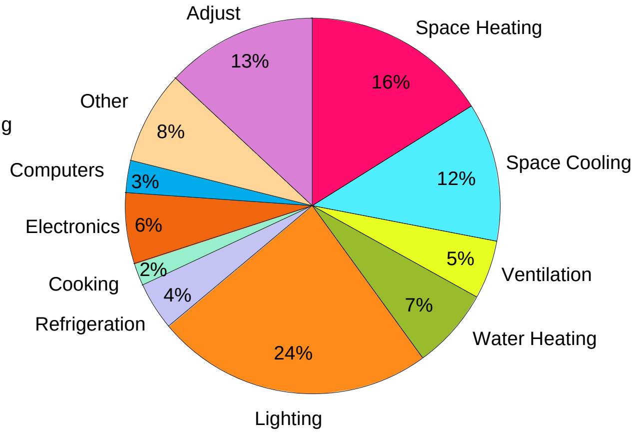

**Figure 8-2. Primary energy consumption in commercial buildings by end use for year 2000. Total primary energy use = 17.4 EJ (16.5 Quads).** *Source: U.S. DOE 2002*

mation Agency) *State Energy Data Report*. In the commercial sector, lighting accounts for about one quarter of total primary energy use, and is far and away the largest identified end-use in this sector. Space heating is next, followed by office equipment, cooling, and water heating. The "miscellaneous uses" category contains cooking, transformers, traffic lights, exit signs, district services, automated teller machines, telecommunications equipment, medical equipment, and other unidentified end-uses. It also includes an adjustment term to ensure that the total commercial sector energy use adds up to the totals reported in EIA's *State Energy Data Report*.

This energy portrait in year 2000 will of course not remain static in the next two decades, and that has important implications for energy policy design. EIA projects in its *Annual Energy Outlook 2002 Reference Case Forecast* [EIA 2001], for example, that energy demand for personal computing and office equipment services in the commercial sector will increase over 4% per year. By contrast, EIA also projects sharp *decreases* in home energy use for refrigeration and freezers, due to implementation of standards and technological improvements. These projected shifts mean that by year 2020 energy demand for refrigeration will have fallen to 5% of total use (versus 9% now), while energy use for commercial office equipment will increase its share from 9 to 14% of that sector.

**Classification of Research Directions:** Major transformations are possible in the energy features of buildings as the result of applied technology R&D and in the underlying basic sciences. In as much as most of these are best applied to new construction, their market penetration will probably occur after the year 2020.

**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.

- Multifunctional 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.

- 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 Green House Gas (GHG) emissions.

Decreasing the building thermal load reduces the need for heating and cooling energy. The following 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 chlorofluorocarbons (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.

**Sensors and Controls:** To best optimize the energy efficiency, air quality, and personal comfort of an entire building, monitoring of the interior space is critical. An essential requirement for effective monitoring will be the development of low-cost, low-power sensors. Poor office environments cost U.S. businesses more than $400 billion a year in productivity losses and increased health care costs. To achieve maximum energy efficiency, a whole-building perspective is needed that integrates sensors, controls, and communications to anticipate changes in the environment and respond dynamically while maintaining comfort and air quality. First-order estimates indicate that such an approach will reduce annual energy consumption by 2.1 EJ (2 quads), reducing energy costs by $55 billion and carbon emissions by 35 MtC [Christian 2002].

## Industrial Sector

**Overview of Sector:** The industrial sector is extremely diverse and includes agriculture, mining, and manufacturing industries. In year 2000, the industrial sector (manufacturing industries only) consumed about 37 EJ of primary energy, accounting for close to one-third of the primary energy consumed in the U.S. that year. As shown in Figure8-3, the most energy-intensive subsectors include chemicals, petroleum refining, forest products (pulp and paper), steel, mining, aluminum, metal casting, and glass. The large electricity component represents the energy lost in conversion to electricity by the electric industry in serving the other industries.

Among sources of energy, the industrial sector heavily favors natural gas and electricity, as shown in Figure 8-4. Losses in energy generation, distribution, and conversion, are substantial; less than half of the total energy input to industry for heat and power is actually delivered to the process.

Figure 8-5 provides a breakdown of the share of $CO_2$ emissions by industrial subsector. Carbon dioxide emissions from industrial energy use as well as process emissions from cement manufacture were 478 MtC, accounting for 31% of total U.S. $CO_2$ emissions [EIA 2001].

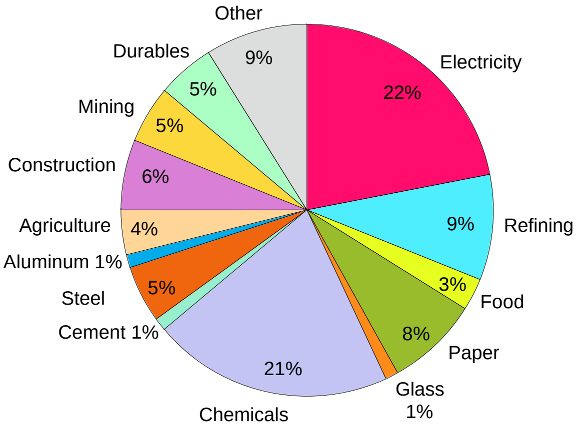

**Figure 8-3. Primary energy use by industrial subsectors for the year 2000. Total primary energy use = 37.5 EJ (35.5 Quads).** *Source: EIA 2001*

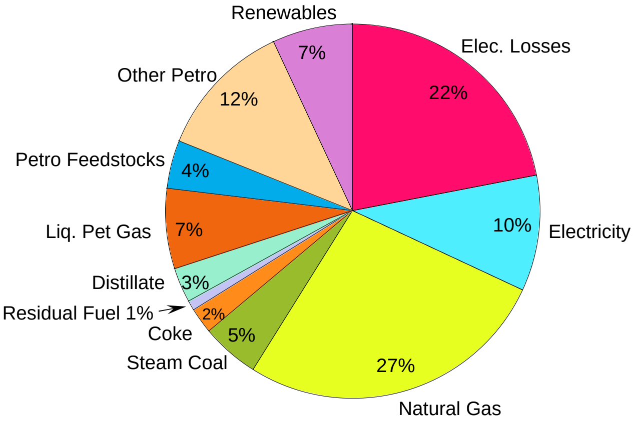

**Figure 8-4. Industrial energy use by source for the year 2000 = 37.5 EJ (35.5 Quads).** *Source: EIA 2001*

## Classification of Research Directions: Overarching Themes

Industrial equipment offers significant opportunities for improving energy efficiency. In the longer term, however, the most substantial gains in energy efficiency will come from changes in systems rather than changes in individual devices. Four major technological pathways for improving industrial energy efficiency have been identified (Figure 8-6). Following a brief discussion of these pathways, opportunities for basic science research in specific industrial subsectors are identified.

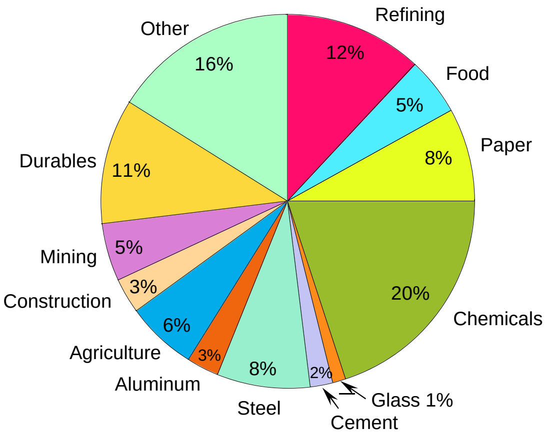

**Figure 8-5. Carbon emissions by industrial subsector for the year 2000 (478 MtC).** *Source: EIA 2001*

***Energy Conversion and Utilization.*** Industrial energy efficiency could be improved by incorporating the best technologies in a systems approach (e.g., advanced turbine systems, improved combustion technologies, and optimal use of thermal energy in a systems approach to plant design). In the longer term, further gains may come from the use of fuel cells and gasification of biomass and in-plant residues.

***Industrial Process Efficiency.*** Revolutionary new processes could greatly reduce the energy intensity of producing primary metals, chemicals, and other products. Numerous technical hurdles involving fundamental science must be overcome for the successful development of such processes. Incremental improvements to existing technology (both industry-specific and crosscutting) yield substantial cumulative energy savings.

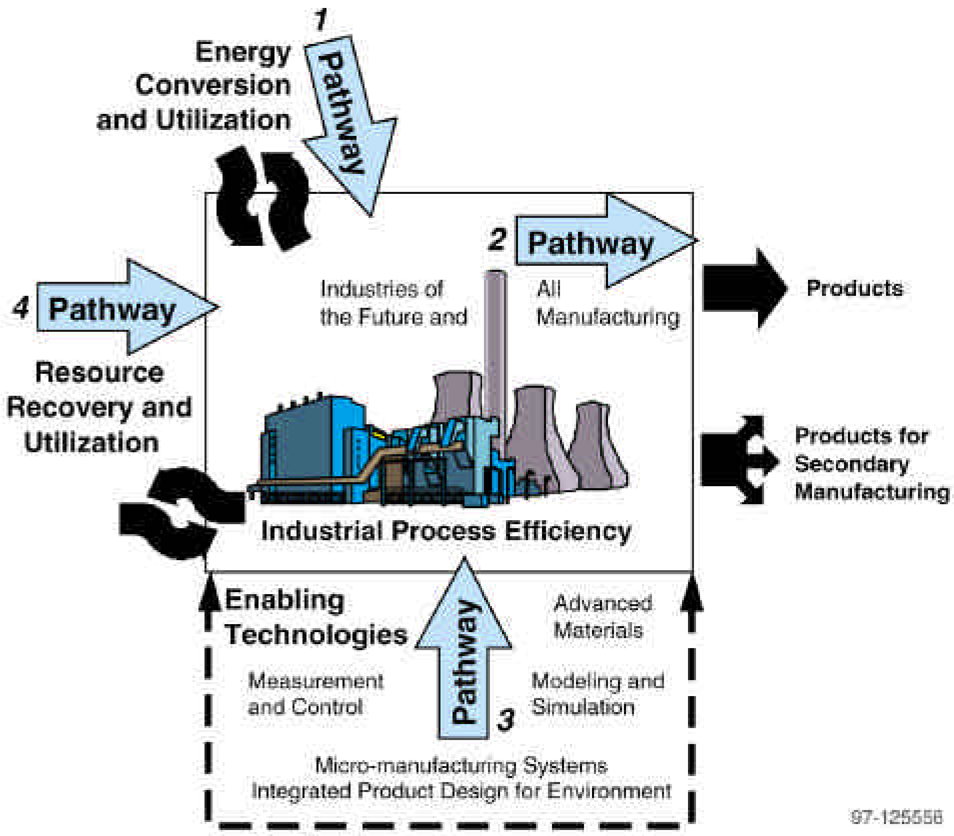

**Figure 8-6. Technology Pathways for Industrial Energy Efficiency**

***Enabling Technologies.*** Advances in information processing and control, materials science, and combustion technologies could significantly improve existing processes *and* could lead to fundamental breakthroughs in the development of revolutionary processes. The greatest opportunities for energy savings include novel information processing techniques, intelligent control systems, and advanced modeling and simulation. The development of better fundamental physical and chemical data on combustion phenomena and other industrial reactions and processes will be required for advanced models and control schemes. In addition, industry needs more efficient combustion technologies and long-life industrial materials capable of withstanding high-temperature and corrosive environments.

***Resource Recovery and Utilization.*** Through technological advances, manufacturers could select raw materials that will eliminate waste discharge or undesirable by-products. Substantial energy savings and greenhouse gas reductions are possible through fundamental changes in the way raw materials are obtained, the properties they exhibit, and the way they are used in the design process.

### Classification of Research Directions: Industry-Specific

Significant reductions in industrial energy intensity (and greenhouse gas emissions) could be achieved through R&D in the underlying basic science of major industrial processes and crosscutting areas. The importance of each industrial subsector to the total energy consumption is presented in Figure 8-3.

***Aluminum.*** The production of primary aluminum using conventional electrolytic cell technology is energy intensive, with an average electricity requirement of 15 kWh per kilogram of output. Although scrap-based aluminum production uses only 5% of the energy used in primary production, there is a continuing need for primary aluminum production. The development of advanced cell concepts such as nonconsumable anodes and wettable cathodes, as well as novel alternatives to electrolysis (e.g., carbothermic reduction), is underway and could result in large energy savings (>25%) and dramatic greenhouse gas reductions. The basic science needed to further these developments include fundamental knowledge on high- and low-temperature salt chemistry, solubilities and conductivities in salt melts, and high-temperature vapor kinetics and gas diffusion characteristics. Downstream processes (including casting, forming, finishing) could be improved through research on alloy development, improved measurement and prediction of physical and mechanical properties, and the development of thermal-physical data for solidification modeling.

***Chemicals and Petroleum Refining.*** The overall U.S. chemical industry consumed about 7.6 EJ of primary energy in year 2000; the most energy-intensive segment is organic chemicals, followed by plastics. Nearly 50% of the energy used within the industry is transformed into chemical products. Petroleum refining, the most energy-intensive manufacturing industry in the U.S., accounted for another 3.2 EJ of primary energy consumption in 2000.

The development of new, energy-efficient processes for performing the separations and reactions in these industries depend on developments in basic science, including:

- *Separations.* High-priority research applications include separations from dilute solutions, bioprocesses, and gaseous mixtures. Distillation R&D needs include predictive methods of mass transfer under various conditions and understanding basic physical kinetics of mass transfer between phases and hydrodynamics of fluids within the column. The greatest improvements in separation technologies are expected to come from new materials (such as resins, membranes, and selective adsorbents) and in the design of new hybrid systems (such as complexation filtration, magnetic filtration, field-enhanced filtration and distillation, reactive extraction and distillation, and membrane reactors).

- *Reaction Engineering.* New process chemistries based on new feedstocks and reaction media will require new equipment and reactor designs (e.g., sonic, micro, photochemical, short-contact). Other needs include experimental methods to observe heterogeneous catalytic transformations and new cells and chemistries for chlor-alkali.

- *Alternative Feedstocks.* New chemistries are required to efficiently convert biomass, unused by-products, and abundant materials such as one-carbon compounds into useful raw materials for chemical processes.

- *New Reaction Media.* Fundamental studies are needed to advance the development of chemistry in alternative reaction media.

- *Catalysis.* New catalysts are needed for reaction pathways focused on ultrahigh selectivity, higher molecularity, longer life, self-reparability, and higher regio- and stereospecificity. Oxidation catalysts for carbon/carbon and carbon/hydrogen bond activation are also needed.

- *Interfacial Science.* A fundamental understanding of the chemistry at interfaces of multiphase systems is needed to develop new chemistries, reactions, and separations processes.

***Forest Products.*** In the year 1998, the U.S. pulp and paper industry consumed 3.0 EJ of primary energy. Most of the opportunities for basic science research are in the area of sustainable forestry. The goal of work in this area is to develop trees with reduced lignin and increased cellulose content, which would save energy and chemicals by reducing pulping and bleaching requirements. Specific needs include better characterization of cellulose to improve recovery of cellulose and polysaccharides, sequencing of active genome of model plant species (Arabidopsis), identification of genes controlling quantitative and qualitative traits in tree species, and understanding of critical limitations to accelerating plant growth. In addition, better understanding of the corrosion mechanics in heat recovery environments could lead to significant energy savings through improved heat recovery in pulp mills.

***Glass.*** Glass production in the U.S. consumed nearly 0.2 EJ in year 2000. The majority of energy is used in relatively inefficient, fuel-fired furnaces to melt glass. Basic R&D needs include the development of high-temperature, corrosion-resistant, long-lasting materials for processing equipment; new methods of heat recovery; and chemistry and tools for identifying gases and properties in order to improve environmental control of the furnace.

***Metal Casting.*** Domestic foundries consumed about 0.4 quad of energy in 2000. Advancements in materials technologies could help the industry optimize its processes while producing superior castings with highly controlled properties. R&D needs include the development of better chemical and physical data on the properties of metals in the liquid and semisolid states, knowledge of alloy-microstructure-chemistry-property relationships, and clean metals technologies. Techniques are also needed to more accurately predict product properties as a function of the casting process used.

***Mining.*** Opportunities for energy savings exist in the areas of exploration and resource characterization, as well as in mining processes themselves. R&D needs include resource characterization technologies, better understanding of the time resolution barrier in geophysics (to improve the accuracy of deep sensing of rocks, minerals, elements, and structures more than 1,000 feet beneath the surface), and better understanding of hydrodynamics of mineral/water suspension and mineral and solution properties and behavior of fine particles in solution.

***Steel.*** The U.S. steel industry consumed 1.7 EJ of primary energy in 2000. Integrated (ore-based) steelmaking is more than twice as energy-intensive as secondary (electric arc furnace) steelmaking. As with aluminum, the limited availability of suitable supplies of scrap dictate a continuing need for ore-based steelmaking. The average energy intensity for the industry overall is currently about 17.5 million Btu/ton. The industry is seeking revolutionary iron and steelmaking processes that will reduce energy intensity by eliminating cokemaking and blast furnace ironmaking. Such processes will require advances in fundamental knowledge and control of the physical and chemical phenomena. In concert with many other industries, the steel industry also needs better data on the thermophysical and thermochemical properties of materials, enabling the development of predictive models and simulations. Similarly, process models for improved control systems could lead to higher energy efficiency in all industrial processes.

***Crosscutting.*** Technologies used throughout industry, such as combustion, materials, and sensors/controls/automation, require enabling technological advances that can improve existing processes and can also spur development of totally new industrial processes and technologies. The high temperatures and corrosive environments of many industrial processes (e.g., ironmaking) have limited the extension of many recent technological advances into these industries, and advanced materials with superior properties are needed. Wireless sensor systems and novel information processing techniques could have widespread benefits, as could improved burner designs and heat recovery techniques.

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