World Energy Council
CONSEIL MONDIAL DE L'ENERGIE

Energy End-Use Technologies for the 21st Century

July 2004

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A Report of the World Energy Council

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Published July 2004 by:
World Energy Council
5th Floor, Regency House
1-4 Warwick Street
London W1B 5LT
United Kingdom

ISBN 0 946121 10 90 946121 15 X

Sponsors and Authors

The study was supported by the Japan Energy Association, the Swedish Energy Agency, the United States Energy Association, and the World Energy Council.

The following provided especially valuable input during the course of the study: Saleh Al-Ajlan, Lucien Bronicki, Latsoucabe Fall, William Fulkerson, Hirohiko Hoshi, Hisham Khatib, Takamori Shiina, Peter Snowdon, and Yoshitaka Sugiyama.

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The assistance of Carol deBruin, Pui-Yee El-Gharras, Marion Friepess, and Yoshihiro Hatano in the WEC London office has been crucial to the completion of this report.

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Foreword

New technologies are at the heart of the three goals of the World Energy Council: Accessibility (hence the need to pay special attention to the technologies that can be used in developing countries for providing commercial energy to those who do not have it), Availability (technology being seen as a means to create a more diverse and secure energy supply), and Acceptability (for more environmental-friendly energy uses).

This Report goes beyond recent WEC work on energy source and conversion technologies to concentrate on end-use technologies and distributed energy, which was not covered in the previous work. The Report focuses on industrial processes, buildings, transportation, and cross-cutting technologies. It also addresses the expected requirements for RD&D investments in these technologies.

As with earlier work, the approach of the study was to build on recent work on RD&D trends, relevant features of global energy scenarios (enriched in terms of end-use by the technologies data bank and company experience of the International Institute for Applied Systems Analysis (IIASA). IIASA scenarios were used to obtain some idea of the high and low ranges for energy end-use and the potential market for new technologies. The model accounts for investment costs, timing, and technology learning as a response to the circumstances described in the selected scenarios. It should be stressed that the approach has not developed new scenarios but complemented earlier work by WEC and IIASA.

Technologies cannot be studied independently from the strategies of the private sector and the institutional framework in which the industry operates. The Report takes into account the focus of specific companies, including automotive companies for the first time, in their technology development work related to the use of energy. A benefit of this approach is to increase the awareness on what the critical issues for technology are from a market standpoint: development of new concepts, availability of financial incentives, the need to overcome institutional barriers.

I am sure that this Report will be a major contribution to our better understanding of the part that new end-use technologies can play on the energy scene. I am particularly pleased that the Japan Energy Association, the United States Energy Association, and the Swedish Energy Agency through the Swedish Member Committee of WEC joined together to help finance this work and to assign reputable experts from around the world to lead the teams that carried out the analysis. In addition to team leaders, Stephen Gehl, Harald Haegermark, Hans Larsen, Masao Morishita, Nebojsa Nakicenovic, and Tuomo Suntola, we owe our thanks to the Study Group and especially its chairman, Dr. Robert Schock, for the high quality of the findings and conclusions in the Report.

François Ailleret
Chairman, WEC Studies Committee
July 2004

Executive Summary

This study examined the potential of energy end-use technologies and of research, development, and demonstration (RD&D) into these technologies on a global scale. The goals of the study were threefold: to identify important technologies for the next 20–50 years that can increase the benefits of energy; to help define the roles that industry and governments might play in their development; and to determine the investments required to bring these technologies to the stage where the marketplace can decide whether they are useful. This is the first attempt to examine the future of energy end-use technologies on a global scale, both geographically and across the energy spectrum. Source and conversion technologies were reported in 2001. While preliminary, it should nevertheless encourage industry and governments to undertake more detailed investigations.

While surprises are likely, current research developments offer a picture of what may happen in the future as new technologies face the competition of the marketplace. Given the vast breadth of energy end-use technologies, the differences between regions and economic conditions, and the limited time available, the Study Group chose to focus on only those technologies that appear most important from today's vantage point.

Several overall conclusions are evident from this study:

- Globally, robust research and development followed by demonstrations of new end-use technologies can potentially save at least 110 EJ/year by 2020 and over 300 EJ/year by 2050. If achieved, this translates to worldwide energy savings of as much as 25% by 2020 and over 40% by 2050, over what may be required without these technologies.
- The success of new end-use technologies—and therefore their ability to affect the marketplace of the future and achieve the World Energy Council's (WEC) goals of *Availability*, *Accessibility,* and *Acceptability* of energy technologies—depends on RD&D investments and policy decisions made today. Key technologies will be available earlier and will impact more and diverse sectors of the global population with early and sustained investment.
- It is almost certain that no single technology, or even a small set of technologies, will dominate in meeting all the needs of the globe in any foreseeable timeframe. A diverse portfolio of RD&D and related policy measures, with specific technology performance targets and market incentives, is required.
- Governments and industry should encourage more in-depth studies than those completed for this WEC report as well as studies of *all* potential technologies. Such studies should be performed *in concert* and from a *global perspective*. In particular, the temporal and geographic deployment of major technologies on a global scale should be studied in detail.

- Governments, in close cooperation with industry, should carefully consider RD&D incentives and policies that can help get end-use technologies from the laboratory or test bed to market. This will involve a careful examination of regulations and incentives for the technologies themselves and the capital markets that will help in their development.

- Absent a significant joint government-industry effort on energy end-use technology R&D (conservatively estimated to cost at least $4 billion per year), the technologies needed will not be ready for the marketplace in the timeframes required by even the most pessimistic scenarios of world economic development.

Short-Term Impact Areas

A number of short-term impact areas are likely to benefit from focused RD&D and have the most impact on the WEC goals. Short-term RD&D is generally done by industry with government playing a supportive role. At the very least, industry leads in the demonstration phase. The following RD&D areas were identified as requiring urgent attention:

- More efficient and less costly distribution and utilization of electricity because electricity is a key energy carrier used in all sectors with a wide-range of technologies.
- Efficient and economical distributed electric-power production to ensure at least 500 kWh per person per year to the rural populations of the world by 2020, and 1,000 kWh by 2050, consistent with the 2000 WEC Millennium Statement.
- Alternative fuels and means for transportation will meet the growing concern—also pointed out in the 2003 WEC study, *Drivers of the Energy Scene*—about the ability of petroleum to meet increasing global transportation needs at affordable prices.
- More efficient power systems for automobiles and trucks that also reduce emissions.
- Improved use of raw forest materials to produce energy more efficiently in the paper and pulp industry.
- Reducing consumption of raw materials and decreasing emissions in the production of iron and steel.
- Improved energy efficiency of the aluminum production process to reduce CO_2 emissions.
- New technologies for the cement industry to greatly increase energy efficiency and reduce pollutants and greenhouse-gas emissions.
- Intelligent systems to optimize energy use in buildings.
- Improved efficiency of cement production and reducing the quantity of CO_2 produced by the process.
- Improved process and separations technologies for chemical production.
- Information and communication technologies integrated into energy end-use services, especially in the developing world.

- Simple, inexpensive cooking methods in poor areas of the world.
- Efficient and economical desalination technologies that will make clean water available to people and industries worldwide.

Longer-Term Impact Areas

For longer-term impact, several technology areas stand out for concentrated RD&D beginning now. These demand more of governments in terms of sustained funding and policies to ensure that promising research is carried through the demonstration phase. Technologies that allow the hydrogen economy to compete in the marketplace may play a crucial role. Benefits include a more diverse energy supply and fewer environmental impacts. These areas include—

- Low-cost and efficient fuel cells.
- Low-cost production, distribution, and storage of hydrogen fuel.
- Hydrogen technologies that foster system synergies (e.g., energy storage of hydrogen to be converted to either electricity or motive power as dictated by demand).
- Above all, technologies aimed at potential niche markets for hydrogen because this fuel is initially very expensive (e.g., an area having inexpensive electric power and abundant off-peak production of electricity).
- Most importantly, integrated multi-task energy systems where multiple end-uses are gained from one fuel or energy carrier. Examples might include integrated hydrogen production, storage, peak electricity generation and motive power, or solar daytime cooking integrated with lighting and biomass fuel for after-dark cooking, or rural electric power, water purification, and telecommunications.

At the outset of the study, the dichotomy between developed and the developing countries became apparent. Developing regions require more fundamental technologies if they are to achieve the WEC goals of *Accessibility*, *Availability*, and *Acceptability*. A number of unanswered questions specific to the developing world warrant further study:

- Can developing regions leapfrog the present industrialized world, or do they simply play catch-up? Correspondingly, how much will the industrial nations' embedded and unamortized infrastructure hinder the adoption of the latest technologies? What role can market reforms play?
- Capital markets have mostly kept up with technology innovation in the industrialized world, and lack of investment capital has held back the developing world. Will this be true in the future or will forces such as globalization change the dynamic? Is outsourcing the beginning of a change in the dynamic? What institutional changes are required?

Part I. Introduction

The World Energy Council's (WEC) 2001 study, *Energy Technologies for the 21st Century,* was aimed at understanding the role that new energy technologies may play in accelerating energy improvements throughout the world—to meet increasingly stringent environmental standards, and to broaden the commercial availability of energy and energy services.[1] That report focused both on research, development, and demonstration (RD&D) expenditures in public and private energy sectors and on the identification of technologies and their associated investment costs for a number of energy source and generation areas that may be significant in the coming century and where RD&D is crucial in bringing them to fruition. Included were power generation, synfuels production, and transportation fuels. Omitted were the energy technologies associated with the end-uses of energy, such as transportation, manufacturing, and buildings.

One objective of this report is to provide a stronger basis for evaluating the energy and policy requirements of end-use technologies and to decrease energy intensity through the introduction of new energy technologies for consumers. However, a comprehensive assessment of all technologies is beyond the scope of this report. Nevertheless, examples of sectors, their most important technologies, and how they might evolve over the next 20 to 50 years are illustrative. A second objective is to estimate the RD&D investments required to ensure that these technologies are available if needed. A conservative estimate suggests that global investment needs for just research and development of end-use technologies approaches U.S. $4 billion per year for a 10- to 20-year timeframe, driven by energy conservation, cost, and environmental considerations. RD&D resources of this magnitude will require public or private consortia to provide funding, as well as industry and government leadership to implement the organization to carry out the required work.

More recently, the Energy Council of Canada strongly advocated the essential role of innovation in energy production, delivery, and use, while elaborating on the crucial role that governments and corporations play in the innovation cycle.[2] Finally, this report attempts to assess the impact of each technology in terms of the goals of *Accessibility, Availability*, and *Acceptability,* as offered in the 2000 WEC Millennium Statement.[3] Thus, the present report must consider the special needs of developing countries as well as the developed world.

A number of pertinent issues encompass the entire end-use sector and require consideration in any discussion of specific end-use technologies. First, end-use technologies cannot be considered to the exclusion of primary energy sources. Cost and availability of primary energy is a large factor in determining the choice of end-use technology. Future energy technologies will be as subject to this basic fact as are those today. On the other hand, end-use technology can create enough demand to drive the development of energy sources. For example, the internal combustion engine has been the principal, although not the sole, driver in maintaining the dominance of petroleum as an energy source.

An energy carrier most often transmits energy from the source to the end-use technology. Electricity, the most ubiquitous energy carrier today, is produced by the conversion of a number of energy sources, the local choice for any carrier being made based on economic, reliability, convenience, and environmental factors. Gasoline carries energy from petroleum (it can also be made from coal, albeit more expensively). Natural gas is an energy source that is also an effective energy carrier and is often used directly with an end-use technology (i.e., conversion to building heat, grid electricity, or transportation power). Coal is more often converted to grid electricity in today's world, although during World War II, there were large-scale conversions to liquid fuel for transportation. Solar radiation may be converted directly into low-grade heat. Hydrogen, which figures prominently in many scenarios for the future because of both its environmental benefits and the efficiency at which it is utilized, carries energy from fossil sources (oil, coal, or gas), from renewable sources (biomass) or by conversion from any source of electricity. Each conversion step involves cost (energy losses and capital costs for equipment) and therefore affects economics. The final benefit/cost calculus ultimately determines market penetration of an energy carrier and its associated end-use technology. Thus, utilizing a cost-effective and efficient energy carrier can promote end-use technologies. **Figure I-1** is a simplified depiction of the dynamic interplay between energy sources, carriers and end-use.

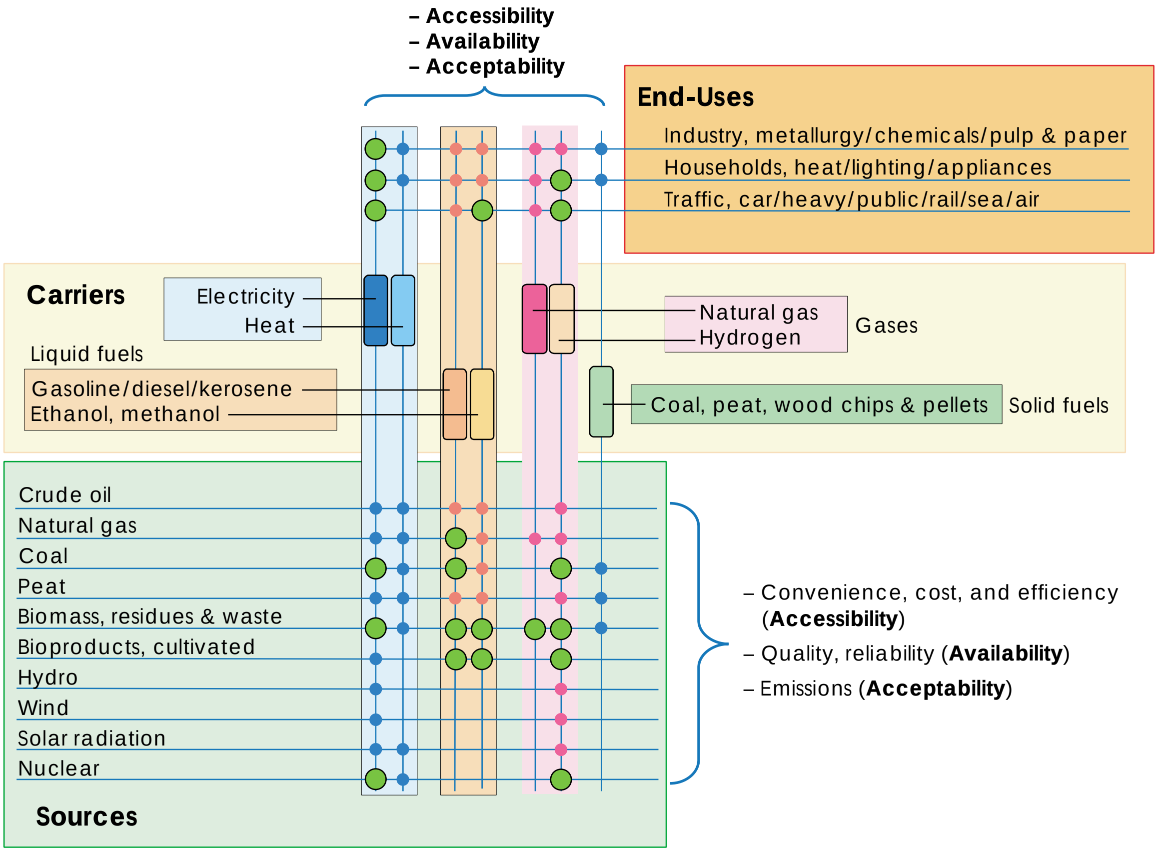

Figure I-1. Conversion of energy sources, through energy carriers and end-use technologies, to end-uses. Green dots represent intersections where potential gains from RD&D may have the greatest impact on the market for end-use technologies, as discussed in Part III (adapted from Tuomo Suntola, Fortum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

Consumer choice follows the market criteria of cost and performance incorporated in the WEC statement: *Accessibility*, *Availability*, and *Acceptability*. In addition, intangible elements of consumer choice, such as convenience, culture, brand reliability, and fashion, can lead to the uptake of technologies that are not necessarily the energy usage optimum or the most cost-effective. For energy companies, the WEC criteria are stressed by economics and the availability of feedstock (primary energy sources). Environmental acceptability is mainly covered through regulations and their indirect impact on economy.

This study is focused on the development of energy technologies for the future. Beyond technology, commercialization in the marketplace usually depends on government policies that—at a minimum—do not hinder their introduction, and—at a maximum—may encourage a more rapid and successful introduction. Governments can influence the introduction of technologies with measures such as targeted incentives, fiscal subsidies, joint incentives with industry, emissions trading, legislated standards, government procurements, and RD&D, among others. All of these have an impact on prices as shown in the recent WEC report, *Drivers of the Energy Scene* (WEC, London, December 2003). But ultimately, technologies will be successfully adopted because while meeting the needs of the public, they add economic value. For government policies to work, it is imperative that industry and governments agree on goals and state them clearly so that stakeholders can make informed choices and develop joint strategies for implementation and deployment. It is also crucial that these strategies are based on sound science and engineering.

Perhaps the most ubiquitous subject across all end-use technologies is efficiency. Cost-effective, energy-efficiency improvements are often overlooked, but they are vital to the sustained use of all energy technology and nowhere are they more important than for end-use technologies. All end-use technologies, therefore, compete on the basis of the efficient use of energy and, because this can be a leading determinant of total cost, it is crucial to the penetration of new technologies into the marketplace.

One of the most important issues for end-use technologies is their impact in and on developing countries. Despite advances in science and technology, the absolute economic gap between developing and developed countries is increasing.* Resolving this discrepancy, where one-third of the world's population lives without access to energy services such as electricity, is a prerequisite for sustained development and a security issue of international dimensions. Without access to electricity, related energy services, and more modern technologies, these conditions cannot be improved. Because there will likely be four to five times as many people in the developing world as in the developed world,[4] an unchanged situation is unstable, with uncontrolled migration across borders as the least harmful outcome and the breeding of international terrorists as perhaps the worst. No other area so represents this less-developed part of the world as Africa, in particular sub-Saharan Africa. Africa contains approximately 13% of the world's population, yet almost half live in extreme poverty on less than U.S. $350 per year. Africa's primary energy use is 0.336 toe (14 GJ) per person

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* Note that on a per capita basis, the gap may in fact be decreasing, as the two largest population countries, China and India, develop their industrial base. See *The Economist*, 13–19 March 2004.

per year in contrast to 8.1 toe (340 GJ) in the United States. Annual electricity consumption is 482 kWh per person versus almost 13,000 kWh in the United States.

What can be done with energy end-use technologies to decrease this gap? How can poor people in developing countries benefit in a practical sense from new technologies? What can be done to facilitate the deployment of suitable technologies to these people? Among overall actions that have been suggested are innovative financial arrangements brokered between industry and government to install appropriate infrastructures to deliver energy, especially electricity, and increasing the priority that government's place on energy improvements. At the same time, energy intensity in the developed world must continue to decrease.

Some energy end-use technology issues specific to developing countries* are—

- The developing world may not have to follow the path already followed by OECD countries. Rather, the latest technology might be immediately implemented in some areas, so-called *leapfrogging*. Yet, fundamental hurdles of capitalization and manpower skills remain. The respective roles of industry and government in developing and enhancing new energy technologies need to be defined.
- Remote stationary electric power generation (Distributed Generation, or DG) has been advanced as a primary need in developing countries. Although not an end-use technology, it is nevertheless integral to the utilization of end-use technologies (see Figure I-1) and offers significant benefits to developing countries, especially in rural areas, beyond the value of electricity alone (e.g., water pumping and purification, surgery clinics, etc.). Sustainable and affordable DG could provide improved power quality and reliability over centralized power generation and transmission, and possibly at a cheaper price. It remains to be seen which alternative, if any, will dominate and in which regions.
- Building-sector needs in developing countries are more fundamental than those in the developed world and building standards are less complicated. Are governments prepared to take the necessary steps to implement adequate standards?
- The concept of mini-mills (scrap iron—electricity-based) for manufacturing steel has been advanced for developing countries. Yet, it is not clear that developing countries are prepared to take advantage of this basic energy end-use technology to assist their economic growth.
- Developed countries supply most of the paper used in developing countries. Because access to paper is usually a basic prerequisite for societal development, the future highest rate of increase in markets for paper is likely in developing countries. However, it is not clear whether this will indeed happen or that the governments of developing countries will recognize and be prepared to deal with this part of the gap.

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* Thoughtful expansions on the subject of energy in developing nations are in T.B. Johansson and J. Goldemberg, *Energy for Sustainable Development: A Policy Agenda*, United Nations Development Program, New York, 2002, and J. Goldemberg, *Rural Energy in Developing Countries*, (Chapter 10), in *Energy and the Challenge of Sustainability*, United Nations Development Program, New York, 2000.

- A promising approach to energy sources, carriers, and end-use technologies in developing countries is community-based services, such as electric power, water purification, wastewater treatment, water delivery, and telecommunication for medical clinics and schools—packaged and financed in an integrated system. Is this a model for the future of developing countries?
- Service industries appear to play an increasingly important role in developing countries in terms of the economy and employment. Witness the strong build-up of a knowledge-based service industry in China and India. Will other nations follow suit? If so, what are the consequences for the development of core industries such as metals and chemicals?

As is obvious from any study of developing countries, clean and abundant water is crucial to the health and well-being of the population and to a vibrant economy. Energy is a prerequisite. It takes electricity to run pumps and purify water, whether it is purifying existing water supplies or desalinating seawater. Thus, an important set of energy end-use technologies are those associated with water use. In this report, we simply make note of this important issue. End-use technologies are available for these purposes, more efficient ones need to be developed, and these considerations need to be taken into consideration by governments and industry. The importance of fresh water can be illustrated by global available fresh water per person having decreased from 20,000 m^3 per person in 1950 to less than 8,000 m^3 today, mostly due to population growth.[5]

An end-use area that is also important is agriculture, especially to developing countries. Agriculture typically accounts for about 6–7% of the global GDP (see Reference 4), and in developing countries, it is reaching 15% in sub-Saharan Africa and 24% in South Asia. Although important end-use technologies involve energy in the agricultural sector, other than the production of fertilizer in the chemical industry, we simply note their existence here. Nevertheless, they must be considered in any strategies being considered by industry and governments. Technologies such as those in fertilizer manufacture, water pumping and conditioning, and biomass improvement are very important.

Finally, information and communication technologies (I&CT) take on critical importance in all areas of human life, including energy technologies, but none more important than end-use technologies. That importance is obvious in the developed world, but I&CT are a necessary first step in giving people and institutions in developing countries the knowledge to identify and provide energy services.*

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

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Part II. Future Scenarios

To place the evaluation of energy technologies in context, industry representation on the Study Group and reviewers encouraged the examination of the range of possible energy scenarios. While the future cannot be predicted, and technology breakthroughs as well as surprises are always a reality, it is possible using those technologies we envision today to look at the historical development of energy technology and well-documented times for technology learning—along with economic considerations, environmental, investment, and other constraints—to gain insights into potential development paths. These types of studies have been carried out by the WEC before.[1,2] These earlier studies, and the 2001 report on source and generation technologies, were updated for this assessment of end-use technologies. We chose 34 scenarios covering a range of economic and environmental conditions. They include the 6 scenarios developed in *Global Energy Perspectives* (GEP) and 28 developed independently for the *Special Report on Emissions Scenarios*.[3] Scenarios do not predict the future. They are a base on which to examine assumptions and test strategies, especially for business.

The current study focuses on two timeframes: 2020 and 2050. The Study Group felt 2020 was close enough that confident extrapolations from the present can be made, and conversely, that 2050 was far enough into the future as to not be constrained by the present. Three extreme scenarios were considered to understand what the high and low demand might be (referred to here as three reference scenarios). Two of the scenarios can be characterized as futures of high economic and energy growth as a result of successful globalization efforts (A in GEP, and specifically both A1 and A3 being high fossil/low fossil), and the other as ecologically driven with reduced energy consumption due to increased efficiency and energy conservation (C in GEP), specifically C2, which contains significant nuclear power. All three—A1, A3, and C2—describe fundamental—albeit alternative—transitions from current energy systems and end-use patterns toward futures characterized by new energy technologies and human activities. The A and C scenarios represent the effective range of possible futures.

The three scenarios are generally described as follows:

- **A1—High-growth scenario that goes beyond conventional wisdom on the availability of oil and gas.** No remarkable developments favoring either coal or nuclear. As a result, technological change focuses on tapping the vast potential of conventional and unconventional oil and gas. Oil and gas could be replaced by coal in this scenario, and for this readers are referred to another scenario (see Reference 2). However, the gross amounts of energy used in end-use sectors are not that different, although specific end-uses may be affected (e.g., liquids from coal replacing oil).

- **A3—High-growth scenario with transition to a post-fossil energy age.** Large-scale use of renewables with intense biomass and a new generation of nuclear technology lead this scenario. The transition is not completed until 2100 when there is an almost equal reliance on nuclear energy, natural gas, biomass, and a new class of renewable energy composed of solar and wind.
- **C2—Reduced energy consumption.** This scenario is technologically very challenging. It assumes unprecedented progressive international cooperation focused explicitly on environmental protection and international equality and aggressive changes in lifestyles toward conservation and non-materialism. A new generation of nuclear reactors is assumed to be developed that is inherently safe with small-scale 100 to 300 MWe installed capacity. To the extent that nuclear cannot provide the needed energy, renewables make up the difference. Fossil energy becomes a transition fuel.

A summary of the scenarios' characteristics is given in **Table II-1**.

Table II-1. Summary of the A and C scenarios from *Energy for Tomorrow's World*, World Energy Council, 2000. (The table has been updated to the base year 2000 from Reference 3).

Scenario	A	C
Population (billions)		
2000	6.2	6.2
2050	10.1	10.1
GWP (U.S. $ trillion, 2000)		
2000	30	30
2050	110	84
Primary energy (EJ)		
2000	420	420
2050	1040	600
Resource availability		
Fossil	High	Low
Non-fossil	High	High
Technology intensity		
Fossil	High	Medium
Non-fossil	High	High
Net carbon emissions, GtonnesC		
2000	6.4	6.4
2050	9–15	5

A. Forces Behind Scenarios

Numerous factors, sometimes called driving forces, influence patterns of energy supply and the provision of energy services. Both energy patterns in the future and the evolution of their underlying forces (e.g., rate of technology change, prices) are highly uncertain. Alternative scenarios describe how the future might develop, based on a coherent and internally consistent set of assumptions about key relationships, driving forces, and emissions outcomes. Energy scenarios in the literature encompass a wide range of future developments that might influence the evolution of energy systems and services. Often they describe transitions toward more sustainable or simply different patterns of energy supply and end-use. Clearly, demographic and economic developments play a crucial role in determining future energy needs. Another fundamental force is technological change. Other factors are diverse, and it is not possible to devise a simple scheme that accounts for all the factors considered and their weighting in the scenarios. They range from human resources such as education, institutional frameworks, and lifestyles to natural resource endowments, vintage capital structures, and international trade patterns.[4]

The scenarios used in this assessment span a wide range of future population developments from the underlying literature. Global population increases from 6.2 billion in 2000 to between 11.3 billion on the high end to 8.7 billion on the low end of the distribution by 2050. The three scenarios share the same median population development. Perceptions about future population growth have changed substantially since the mid-1990s. At that time, median population projections were well above 10 billion by 2050,[5] while today they have declined to just under 9 billion by 2050.[6] The full range of so-called "probabilistic" projections has declined as well over the same period, from between 8 and 12 billion by 2050 in the mid-1990s to between less than 7 and 11.5 billion in 2050 for the most recent projections. The full range of probabilistic projections is the degree of uncertainty associated with future demographic development. The main reasons for the decline both in the median projections and the associated uncertainty ranges are related to ever-declining fertility rates in the world that have already reached levels well below replacement throughout most of Europe, the United States, and Japan. The extent and structure of future populations are crucial for the evolution of energy systems and technologies in the three reference cases that share the same population development.

Economic growth is closely linked to energy and technology developments, and energy technologies can be considered an essential enabling factor for further social and economic development in the world. All scenarios used here consider a future where per person income increases in the world, but at varying rates across world regions and individual scenarios. In all, there is some degree of conditional "catch up" between developing countries and already industrialized ones. This conditionality refers to relative ranges of growth and not to absolute per person income disparities that continue to grow even in the scenarios with a highest degree of relative "convergence" (see Reference 3).

The historical global world product (GWP) growth rate has been about 4% per year since the 1950s. Across the scenarios examined here, the average growth rates to 2100 range from 1.1% to 3.2% per year, with the median value of 2.3% per year. This translates into a GWP in 2100 that varies from 3.5 to more than 32 times the GWP in 1990. The 1990 and 2000 GWP were about U.S. $20 trillion and U.S. $35 trillion, respectively. These translate into a range of about U.S. $70 trillion to more than U.S. $640 trillion (in 1990 dollars) by 2100. The full range of GWP development in the scenarios' literature includes a few outliers, while the rest of the scenarios are grouped much more closely, compressing the range to a proportional increase of about 7 to 17 times compared with 1990.

A "stylized fact" incorporated in many of the scenarios is that higher rates of economic development are generally associated with lower rates of population growth and higher rates of capital turnover and consequently lower energy intensities. This is based on historical evidence and scenarios in the underlying literature. The main implication is that large reductions of energy intensities and higher rates of economic development demand more rapid and pervasive diffusion of new and advanced energy technologies, and especially end-use technologies.

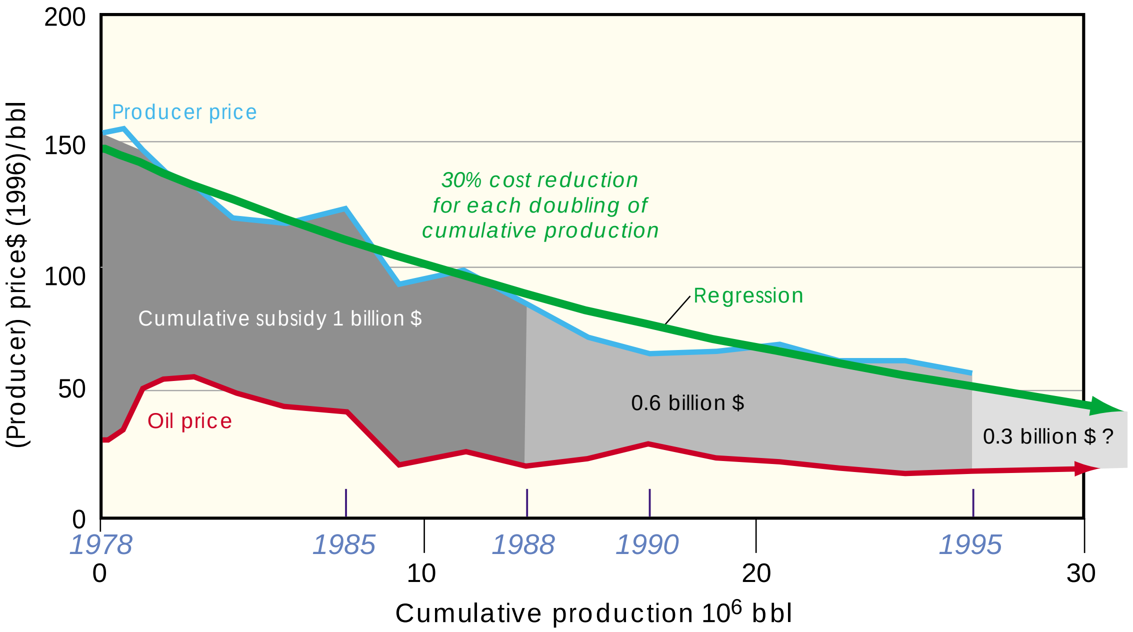
B. Technological Change

Two basic forms of technological change are embedded in the energy scenarios. First, technologies change incrementally over time. That is, technology characteristics improve gradually. Examples of such improvements are reductions of cost, improvements in efficiency, and reductions of emission per unit activity. The second form, more radical, represents an introduction of completely new technologies at some future point in time. Examples are fusion energy or carbon separation and storage from fossil-energy sources. Schumpeter was the first to distinguish between these two basic types of change.[7] The main difference of the Schumpetarian approach with respect to energy scenarios is that technological change is usually treated deterministically in any given scenario. The technology is simply assumed to become available by a certain time period with a given cost and performance, whereas in reality it is an uncertain evolutionary process. Some technologies are successful while others fail, and their costs and performance are functions of many interacting factors. This is the reason for taking a set of scenarios from the literature and assessing the consequences of different directions of technological change across them. The basic assumption is that the range will encompass much of the inherent uncertainty through the richness of alternative futures. Gradual and more radical types of technological change lead together toward transitions described by alternative scenarios.

Another important feature of technological change is that it is cumulative. Small changes are amplified into more fundamental ones as new successful technologies are adopted and replace older alternatives. For example, new technologies are often more costly and inferior compared with the older and more mature alternatives dominating the market. However, new technologies often improve as both producers and consumers gain experience (producers learn by doing; consumers learn by using). Costs and environmental impacts are reduced while other aspects of technology performance are usually also improved. Such gradual and persistent improvements are sometimes correlated with cumulative experience and are referred to collectively as "increasing returns." Empirical relationships between performance improvements or cost reductions with increasing cumulative output or capacity are called "experience" or "learning" curves in the literature. **Figure II-1** shows such a cost-reduction learning curve for ethanol production from biomass in Brazil. The cumulative nature of technological change is one of the fundamental drivers of alternative energy transitions across the scenarios used here.

C. Energy Sources

For the reasons stated in Part I, primary energy sources—although not the focus of this report—are important to end-use technology and are described briefly here. The scenarios analyzed in this assessment encompass a wide range of future energy use in the world and thus test the possible role of future energy technologies under different circumstances. On one side of this range are scenarios with very high-energy usage (up to six times current levels), and on the other scenarios with a high degree of energy savings and conservation that cap future energy needs at less than twice current energy use. Clearly, scenarios with a high-energy use imply different energy technology portfolios compared with scenarios that emphasize end-use energy savings and enhanced performance of energy services.



(Data: Goldemberg, 1996)

Figure II-1. Learning curve for ethanol production in Brazil compared with world oil prices. [Sources: Grübler, personal communication, based on data from J. Goldemberg, "The evolution of ethanol costs in Brazil," *Energy Policy*, Vol. 24 (12), pp. 1127–28, 1996 and reprinted in N. Nakicenovic and K. Riahi, "An Assessment of Technological Change Across Selected Energy Scenarios," *Energy Technologies for the Twenty-First Century*, World Energy Council, London, 2001.]

Figure II-2 shows the range of future primary energy use across the scenarios. The highest energy use approaches primary energy levels of 3,000 EJ per year while the lowest stay below 800 EJ by 2100. Even though this report focuses on 2020 and 2050, scenarios out to 2100 are shown in this section to give readers a firmer grasp of the dynamics and to emphasize the technologies that may become important beyond 2050. The six GEP scenarios share three levels of primary energy use. The other 28 overlap with the six GEP over the lower range, but extend the upper part of the distribution considerably. This is primarily due to the high rates of economic development in some of them. It is interesting to note that the scenarios in the lower range represent sustainable futures with a transition to very efficient energy use and high degrees of conservation. These are also for the most part the scenarios in which energy sources with low carbon intensity play an important role.

Figure II-3 illustrates alternative energy-systems structures across the range of 28 scenarios and historical development since 1850. Relative shares of different energy sources, in percent, show the historical evolution of the global energy supply since the 1850s. The first transition of the energy system started with the introduction of coal that replaced traditional sources of fuel wood and working animals. This transition lasted about 70 years

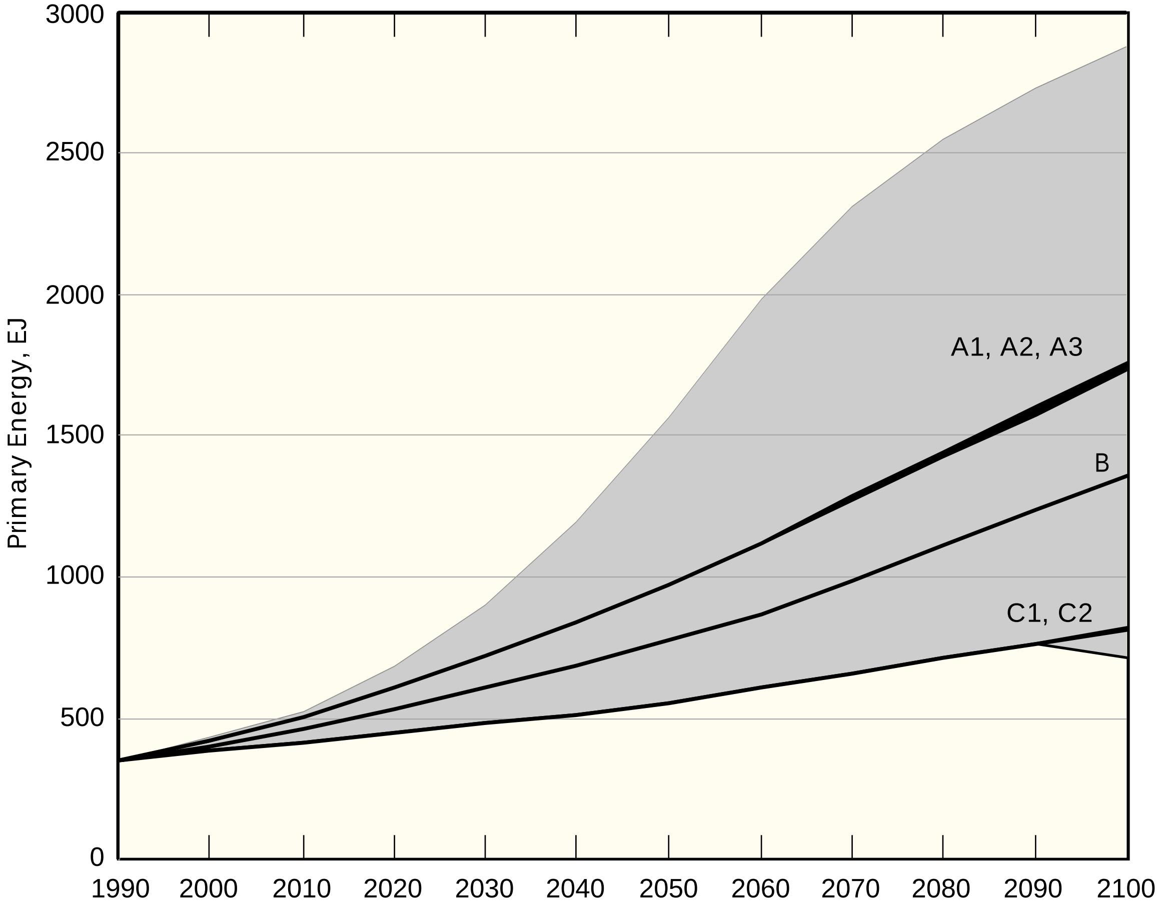


Figure II-2. Global primary energy use. The three cases of energy use are shown for the 6 GEP scenarios (labeled in black) and the range for the remaining 28 scenarios.

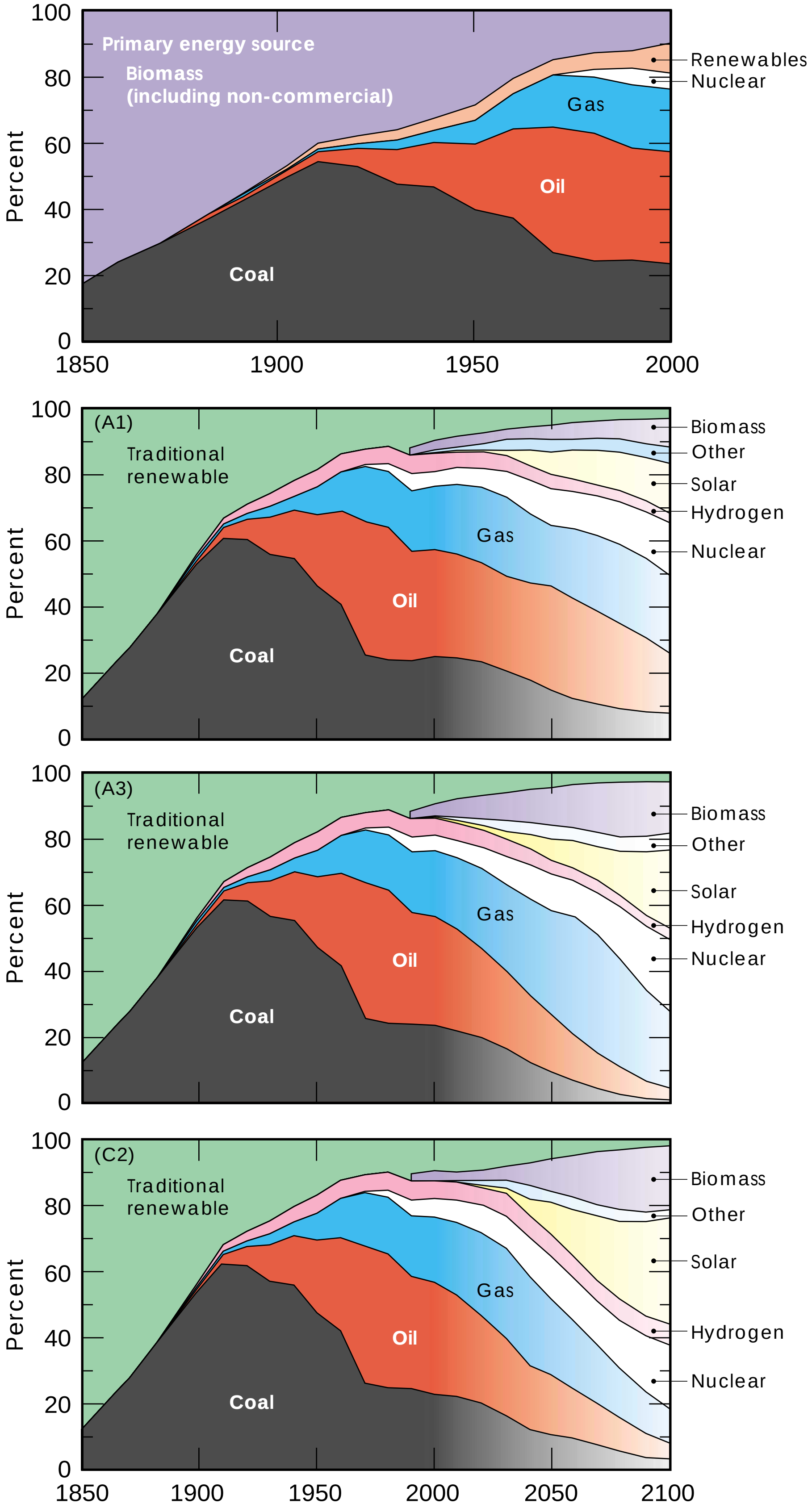


Figure II-3. Historical evolution of energy-systems structures, as shares of different primary energy sources from 1850 to 2000 (top). Future developments for the scenarios used here: A1, A3, and C2 (Sources: Nakicenovic, et al., 1998 and 2000).

until the 1920s. During that period of time, the share of coal increased from 20% in 1850 to more than 60% by 1920. This development phase was characterized by the introduction of steam, steel, and the railways. The next transition lasted another 70 years and is characterized by the replacement of coal by oil and natural gas. It can further be characterized by the rapid expansion of internal combustion, electricity, petrochemicals, and the automobile. By the 1990s, more than 80% of global energy was supplied by hydrocarbon sources, that is, coal, oil, and natural gas. Zero-carbon sources such as hydropower and nuclear play only a limited role today, while traditional renewables supply the rest of the energy needs, especially in the developing countries.

Looking to the future, different possibilities unfold across the scenarios. Some of the scenarios shown in Figure II-3 foresee a return to coal. This is especially important for those regions of the world that have ample coal resources (India and China). Other scenarios emphasize a stronger reliance on oil and gas, while yet other scenarios foresee a transition toward zero-carbon sources with a much stronger role being played by nuclear, solar, modern biomass, and other renewable energy sources. The scenario in Figure II-3d would lead to a dominance of non-carbon energy sources by the end of the 21st century. This transition toward a “decarbonization” of the global energy system at the same time achieves many goals of sustainable development. These are some of the salient ancillary benefits of decarbonization and deep structural changes in the energy system.

Despite enormous differences across the scenarios, they have common features. For example, they share the same assumptions about the availability of fossil- and nuclear-energy resources and renewable-energy potentials. But their deployments differ, depending on assumptions about rates of technological learning, economic development, and other forces (e.g. different levels and directions of assumed RD&D expenditures across the scenarios lead to higher investment in some new technologies and lower in others, promoting cost reductions and performance improvements in some and hindering others. This way alternative energy system structures evolve across scenarios. Another example is the investment in transferring resources into economically viable reserves, again a function of intervening investments. Finally, energy infrastructures tend to have an equivalent lock-in effect.) These differences tend to be amplified after 2020. Because of the long lifetimes of infrastructure, power plants, refineries, and other energy investments, there will not be a sufficiently large turnover of such facilities to reveal large differences in the scenarios before 2020.

These deep structural differences among the scenarios indicate that the long-term global energy futures are not preordained. The imminent resource scarcity forecast in the 1970s for the end of the century has not materialized. With continued exploration efforts and technological progress, accessible and affordable reserves have increased (conversion of resources to reserves), although often at higher cost. After 2020, all scenarios describe transitions away from the current reliance on conventional oil and gas, but to varying degrees. In fact, the currently estimated conventional oil and gas resources do not reach much into the post-2020 periods in any of the scenarios. Most of the divergence across the scenarios after 2020 will depend on technological developments implemented between now and then (see Reference 2).

D. Technology Implications

In contrast to the rich diversity of future energy supplies across the scenarios is a surprising degree of convergence in the structure of the end-uses of energy. This convergence is related to an increasing push for more flexible, cleaner, and convenient forms of final energy and energy services. In general, the quality of energy services improves across all scenarios to a degree independent of alternative primary energy transitions.

Figure II-4 shows the evolution of final energy forms in the world for the three GEP reference scenarios. Today, about one-third of final energy reaches consumers in solid form, e.g., as coal and biomass. This is the primary cause of many local, regional, and indoor air-pollution problems associated with traditional energy uses. One-third reaches consumers in liquid form, consisting primarily of oil products such as oil products used in transportation. The final third reaches consumers through grids, consisting of electricity and energy gases (mostly natural gas). The shares of grid-oriented energy carriers increase across all scenarios to about one-half of all final energy by the end of the century.

Electricity and natural gas continue to increase within this overall transition toward a more important role of grids, and new energy carriers such as hydrogen become ever more prevalent only toward the end of the century. The role of liquids stays roughly the same

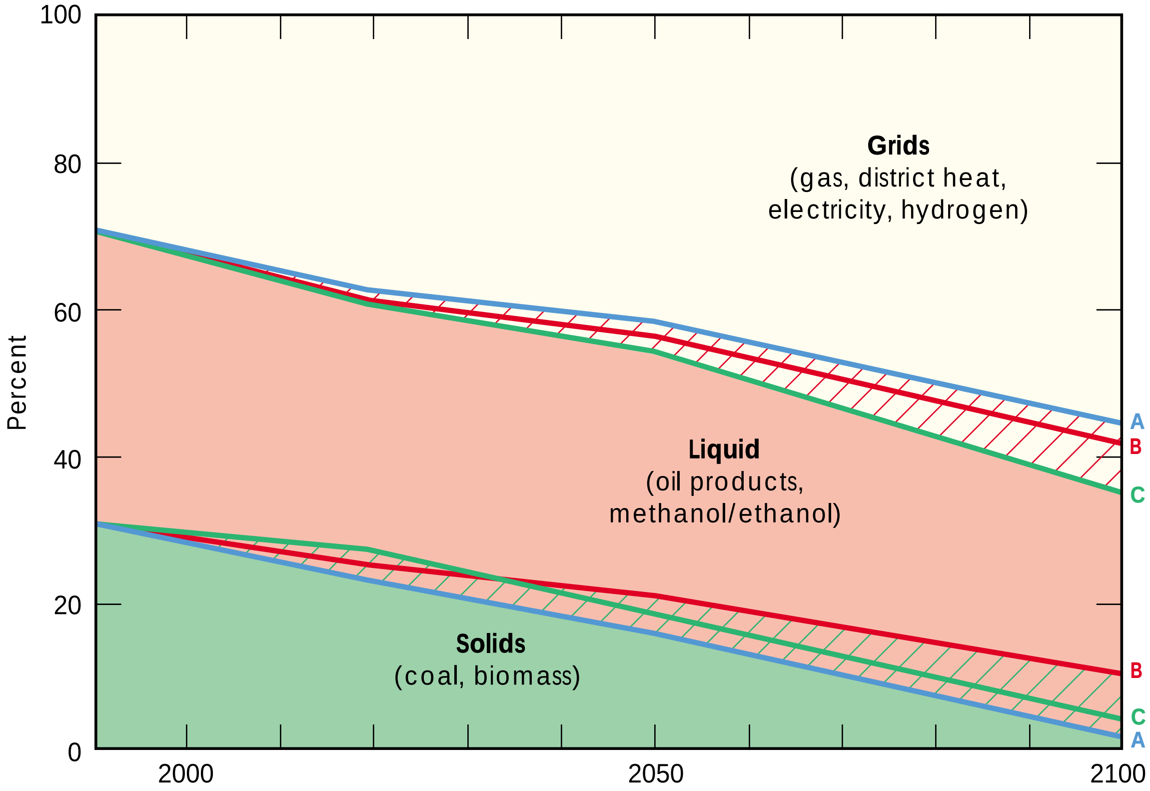


Figure II-4. Final energy across scenarios showing a gradual shift toward gird-oriented energy carriers and away from the direct use of solids, which are instead converted to synfuels, electricity, and energy gases (Source: *Global Energy Perspectives*, Nakicenovic, et al., Cambridge University Press, United Kingdom, 1998.)

with a gradual transition toward synfuels, such as methanol from coal and ethanol from biomass. The most striking of all transitions is the radical decline of solids. This leads to an important reduction of adverse environmental and health impacts. Solids are increasingly converted to electricity, energy gases, and liquids.

Figures II-5, II-6, and **II-7** depict equivalent changes in the primary energy structure for the three reference scenarios and three main economic sectors: industry, residential (household) and commercial, and transportation. This illustrates variations of the overall converging trend in energy transformations toward ever-higher quality, flexibility, and environmental compatibility of final energy carriers. They also illustrate the changing nature of energy services and the technologies that provide them.

Figure II-5 compares the global changes in final energy across all scenarios with those in the industrial sector for the three reference scenarios. It confirms the overall tendency toward lower shares of direct use of biomass and coal in industrial processes and toward higher contribution of modern energy carriers.

In contrast, Figure II-6 shows a dramatic shift away from solids in residential and commercial sector. They are the predominant energy forms in most of the developing regions today, accounting for close to 40% of all final energy deliveries in this sector. The growth of electricity as the energy carrier of choice is predominant in all three scenarios, with synthetic liquids and gases a close second.

Finally, Figure II-7 displays a dramatic shift away from oil products toward synfuels in the transportation sector. Hydrogen becomes a more important energy carrier but only toward the end of the century. As in industry, this transformation is based on the underlying change in the end-use technologies from current reliance on internal combustion engines for road transport and gas turbines for air transport. The exception is rail transport that mostly relies on electric propulsion. The importance of electricity grows across the scenarios, while synfuels, both liquids and gases, become more important in the future. This correlates with a shift toward fuel-cell vehicles and/or other interim alternatives, such as hybrid vehicles.

All of these changes imply a deep and fundamental replacement of current end-use technologies by one and in some cases two generations of new and innovative technologies by the end of the century. The changes are less dramatic by 2050, but nonetheless are very deep compared with the current structure of end-use technologies. This implies a significant amount of RD&D on these technologies before 2050. Scenarios serve here to outline some overarching and pervasive developments. In particular, they help identify possible ranges of the deployment of new technologies and the extent of the substitution of the current generation of technologies. These brief end-use technology descriptions show to what extent some of the new and advanced technologies are deployed in the scenarios by 2050.

As an example of the fundamental end-use technology transformations, **Figure II-8** shows the ranges of final energy carriers used across all scenarios by 2050. Today, oil products are the dominant energy form in transportation, accounting for 90% of all energy needs. This is

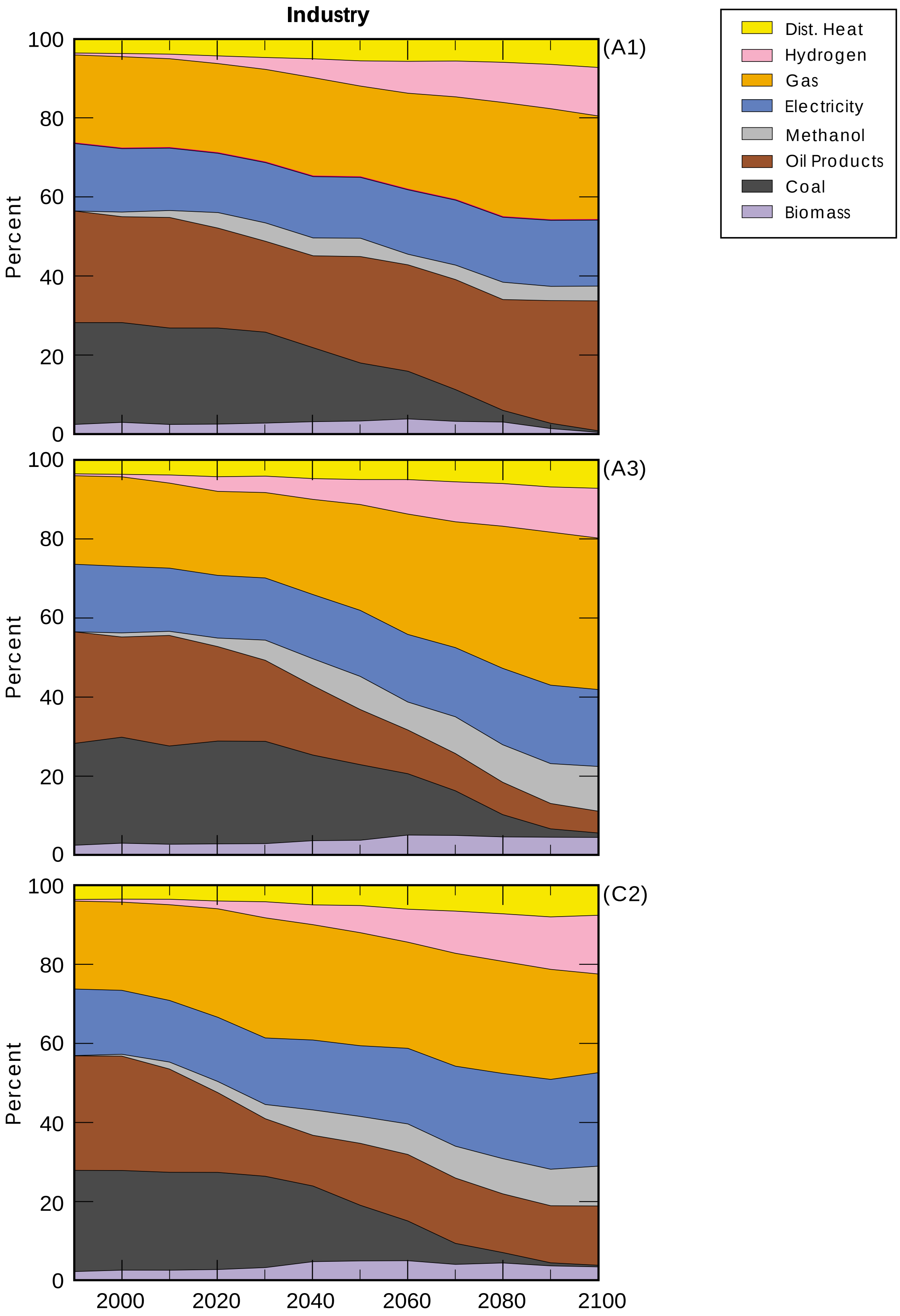


Figure II-5. Global changes in industrial end-use energy for the three reference scenarios.

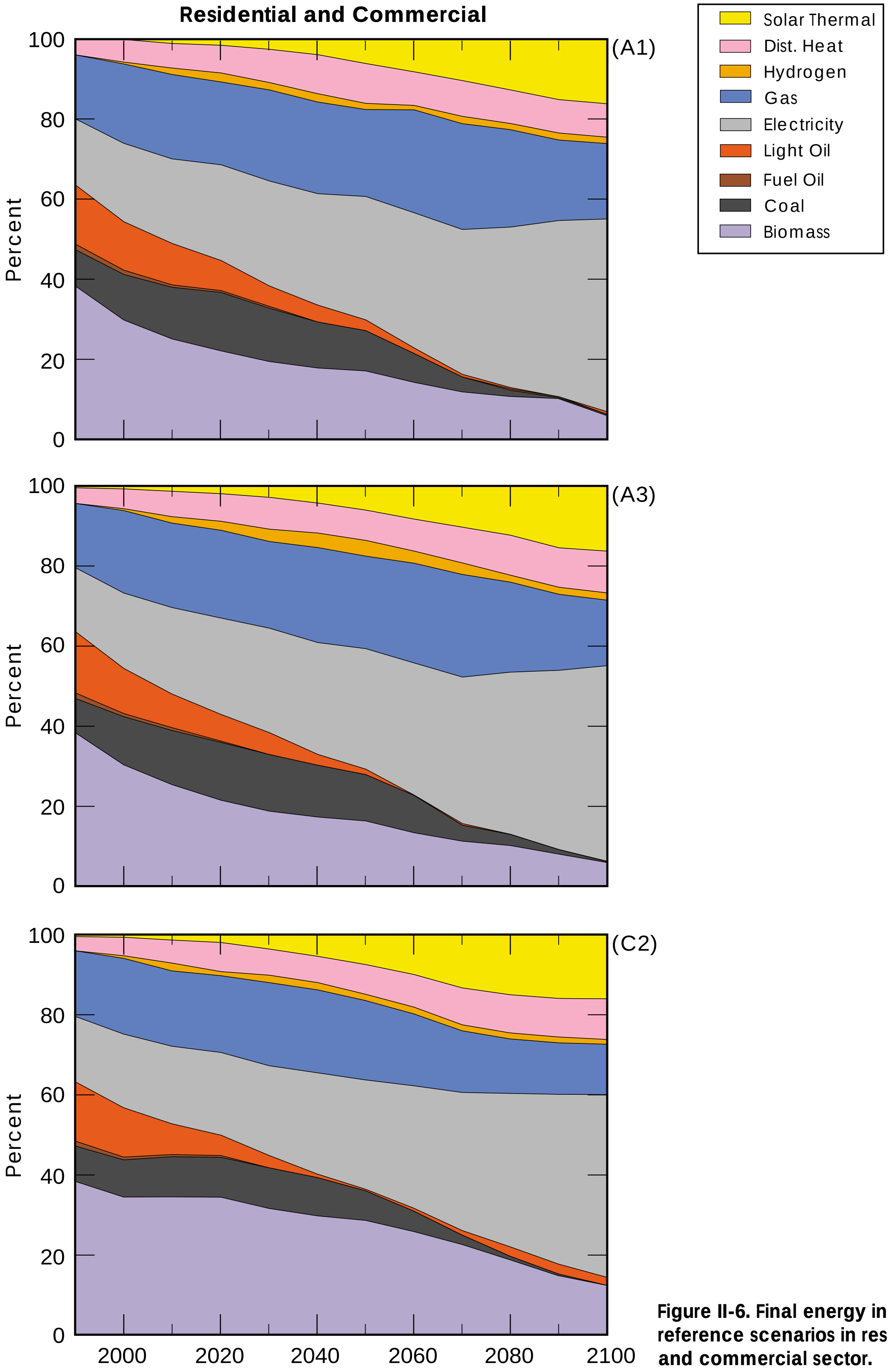


Figure II-6. Final energy in three reference scenarios in residential and commercial sector.

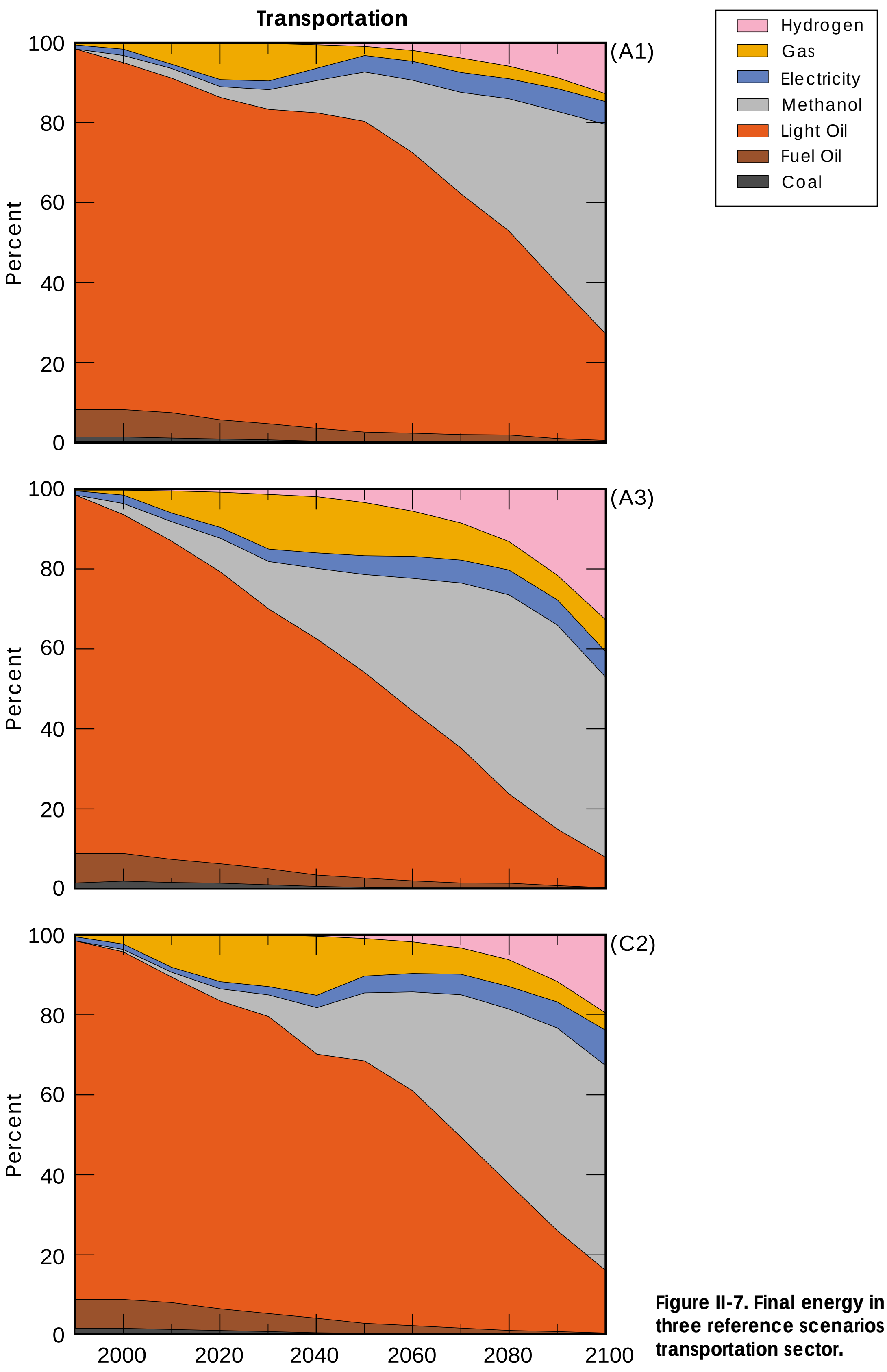


Figure II-7. Final energy in the three reference scenarios for the transportation sector.

a testament to the importance of internal combustion engines and gas turbines. Figure II-8 also shows that oil products range between 50 and 180 EJ by 2050, compared with the total current final energy requirements in the world of some 300 EJ. The median is above 100 EJ or a third of total current final energy. Methanol becomes more important in some scenarios, as for example biomass-derived liquids driven by environmental factors, while it is not as important in others. The median is significantly smaller than oil products. The ranges of ethanol and hydrogen are comparatively smaller. Nevertheless, some of the scenarios imply a radical transformation of the future transport systems, from the current reliance on oil products to a larger share of alternative fuels and alternative vehicles.

In general, a review of the scenarios reveals the following insights:

- Most large-scale changes in end-use sector fuels take place after 2050, regardless of the scenario. Nevertheless, important inroads into the marketplace take place sooner in order for these changes to occur.
- Key technologies are those improving energy efficiency, renewable energy, and the next generation of fossil and nuclear (fission) energy.
- RD&D carried out now is crucial to the realization of any scenario. Accumulation of experience (technology learning) is vital and this takes time.
- In the early stages of RD&D programs, cooperation (as between industry and government) is important to ensure interruption-free technological progress with minimal redundancies.
- Gases—first natural gas and then hydrogen—gradually replace solid and liquid fuels. Hydrogen, while making significant inroads before 2050, predominates only after. A principal reason is that natural-gas conversion and utilization technologies are already well advanced.

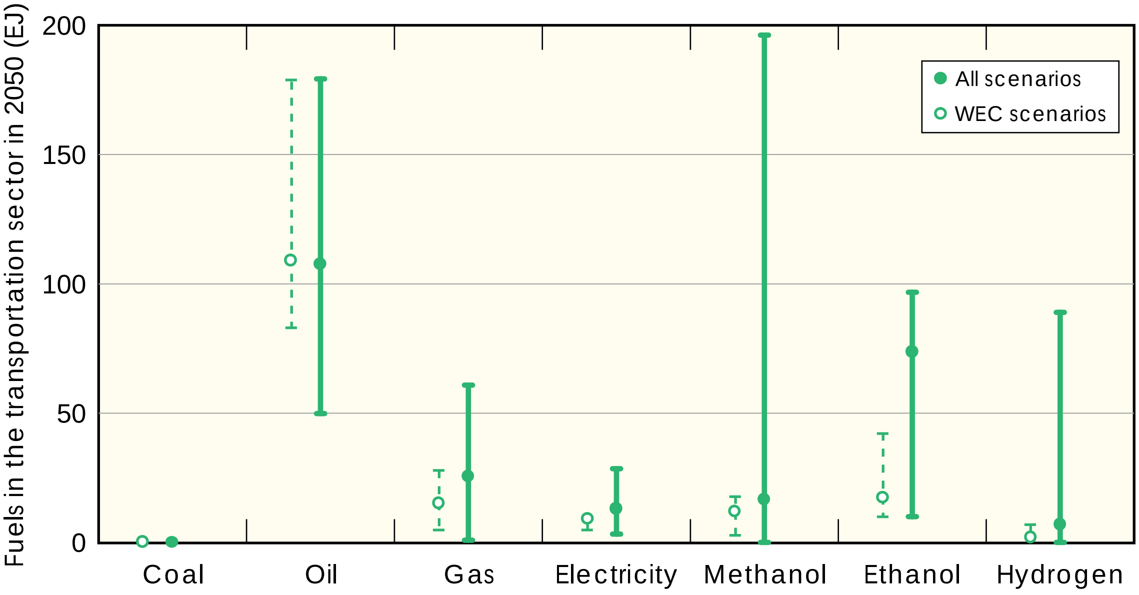


Figure II-8. Deployment of final energy in transportation across all scenarios for the year 2050.

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Part III. End-Use Technologies

The study was divided into four parts covering technologies in the Industry, Buildings, and Transportation sectors, and Crosscutting Technologies (those technologies that crosscut all end-use sectors). Several RD&D areas emanating from the needs of various sectors are common to other sectors.

We have been guided by and gained useful insight from a 1997 study on energy technologies for the reduction of carbon emissions.[1] Each end-use technology area is discussed in terms of the following critical items:

System Concepts
Technology Description
Technology Status
RD&D: Goals and Challenges
Commercialization and Deployment

Benefits and Costs (expected benefits in terms of—)

- Accessibility
- Cost (will it be affordable?)
- Efficiency (will it improve?)
- Availability (will it be more available in the future?)
- Reliability (how does it compare to present competition)
- Energy quality (how does it compare to present competition)
- Acceptability

Risk Factors (scale of 1–10, 10 being extremely high risk)

- Technical (probability of commercialization)
- Commercial (hindrance of deployment)
- Environmental (adverse effects)
- Regulatory (regulation hurdles)

A. Industry

Currently, industry consumes 30% of the world's energy. The scenarios in Part II indicate the industry sector worldwide using 130 to 180 EJ per year in 2020 compared with 115 EJ in 2000. The range represents the difference between the C and A scenarios. In 2050, the scenarios indicate 165 EJ for C and 285 EJ for A, a 143% to 250% increase over today's usage. The energy savings due to new technologies, estimated by taking the difference between the A and the C (reduced energy consumption) scenarios can be as much as 50 EJ per year by 2020 and 120 EJ per year by 2050, with over 80% likely to be achieved in Asia.

This section evaluates energy-intensive and power-quality-intensive technologies. The role of the latter is growing, particularly in the industrialized world. Looking to the future, industry will have to address the need for an improved power-delivery infrastructure to support the special needs of digital loads. The basic task is evaluating energy end-use parameters and opportunities for improving the efficiency, productivity, the working environment, and general convenience. The Study Group focused on manufacturing, process, and knowledge industries, including new and emerging industries. The latter are discussed in Part III.D (Crosscutting Technologies). The work scope also focused on service industries, which constitute up to 60–70% of the GDP in developed countries. Concepts such as the “office of the future,” with its reliance on digital technology show how service industries will evolve to meet the changing needs of the service economy. An evaluation of the potential for technology leapfrogging by developing countries able to bypass some of the laborious technology development pathways already followed by today’s developed countries was also considered important. This would shorten development time and reduce the need to replace embedded infrastructures. The end-uses of electricity instead of other energy forms, and natural-gas processing of materials without using electricity, were also considered.

In examining industrial technology, this section relies heavily on examples. The United States industry dominates several of the industries described and provides many examples. Sweden is also used because it is a small, industrially advanced country with major energy end-use industries, with large export shares, a rapidly growing service industry, and accessible data. Industries examined in this report are Paper and Pulp, Iron and Steel, Aluminum, Electronics and Semiconductors, Cement, Chemicals, and the Service Industries. Together, these represent the vast majority of energy consumption by industry worldwide.

1. Paper and Pulp

The diagrams and data in this part of the report are based on figures and accompanying notes produced by the Swedish trade association, Skogsindustrierna.[2,*]

System Concepts

World paper production has increased steadily for at least 50 years and this trend is expected to continue (**Figure III-1**). Present annual production is about 300 million tonnes as compared to 120 million tonnes in 1970. World pulp production is about 180 million tonnes. Access to paper is a fundamental requirement for societal development. It has been estimated that 40 kilograms of paper per person per year is the minimum amount to meet basic communication and literacy needs. Present average annual consumption is still below 15 kilograms per person in many parts of the world.

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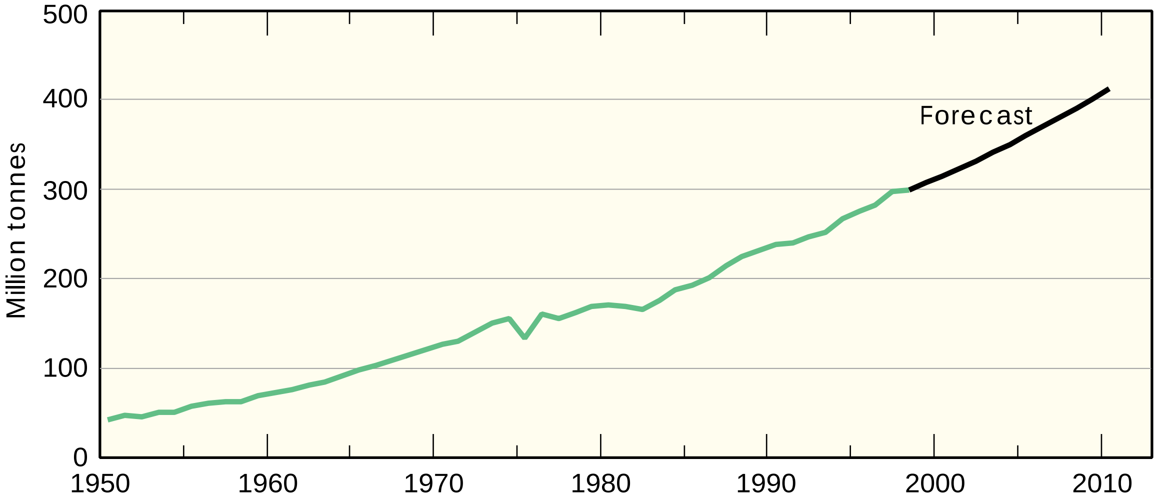
[*] The figures in some instances are based on data from the Finnish paper industry consultant, Jaakko Pöyri.

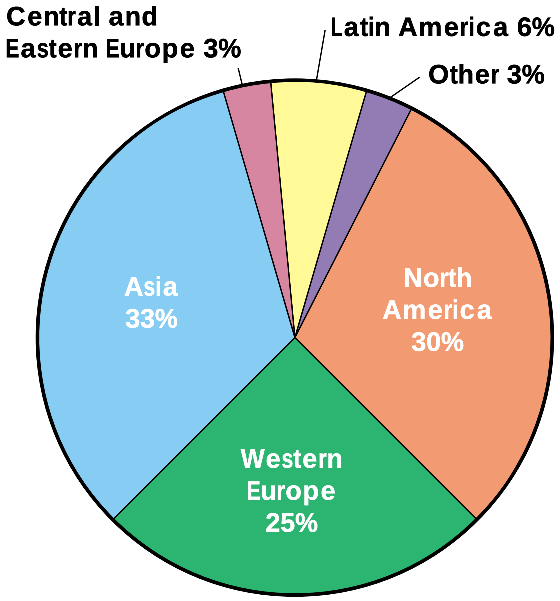


(Source: Jaakko Pöyri)

Figure III-1. World paper production and projection.

The paper and pulp industry, an important part of the economy of the largest producing countries, is very energy-intensive. In the United States, it ranks eighth in manufacturing in terms of GDP. It is even more important in Canada, Sweden, and Finland, both in terms of GDP and as a major export. In the United States, it is responsible for about 12% of manufacturing energy use.[3] In Sweden, it is responsible for almost 50% of the total industrial energy consumption and about 40% of industrial electricity consumption. Costs for energy purchased externally lie in the range of 15–20% of total production costs. It should be noted that the industry uses considerably more energy than appears from these figures because both heat and electricity are generated as an integral part of the production process.

Paper consumption per capita is unevenly distributed between the regions of the world. There are claims that it is one of the few base products that does not yet show saturation in per capita demand in highly developed countries, such as the United States. As an example, the annual consumption of printout paper for personal computers has been estimated at 115 billion sheets, corresponding roughly to 0.5 million tonnes worldwide. Thus, per person consumption is still increasing in the developed world, although at a slower pace than before. In the United States, it increased at 1.8% per year from 1960–1980, 1.6% from 1980–1993, and is projected at 0.6% per year to 2040. In China, paper consumption, although low now, is increasing rapidly. Chinese pulp production was 17 million tonnes in 2001 as compared with 38 million tonnes for the whole of Asia in 1996 (**Figure III-2**). On the average, about 52 kilograms of paper per year is used per person around the world (**Figure III-3**).



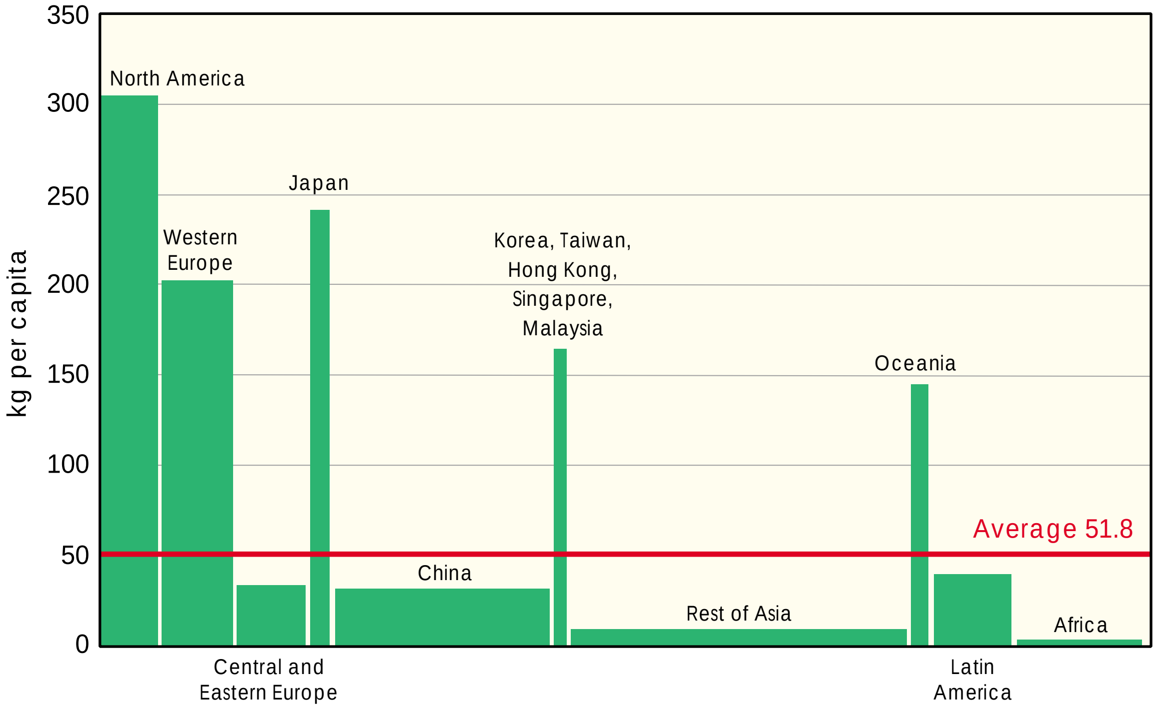
Total consumption: 318 million tonnes

(Source: PPI, 2001)

Figure III-2. Global distribution of paper consumption.

Since 1980, the combined share of paper production from North America and Western Europe has decreased from 67% to 62%, whereas the combined share from Latin America and Asia (excluding Japan) has increased from 11% to about 22%. The industry expects this trend to continue. It also expects production to focus more toward the regions of faster consumption growth. Asia should continue to be a major growth area.

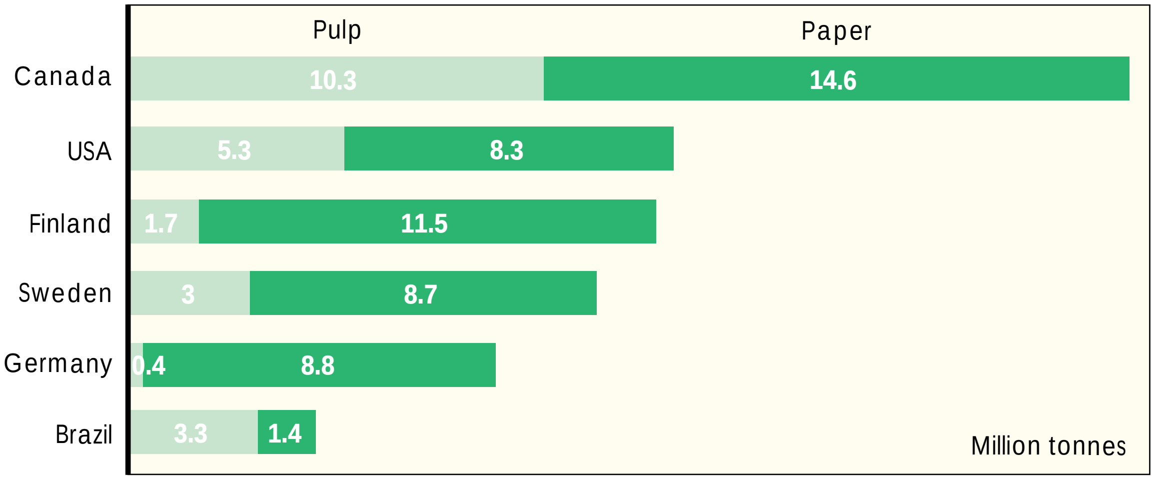
The distribution of world pulp production (179 million tonnes in 2001) is shown in **Figure III-4**. The United States, Canada, China, Finland, and Sweden are the largest pulp producers. Most countries export a relatively small share of their pulp production. Global exports amount to 36 million tonnes or about 20% of the world's production. Normally, a large



(Source: PPI, 2001)

Figure III-3. Worldwide per person paper consumption in 2001. The width of each bar is proportional to the population of each region or country.

share of pulp production is converted to paper in the country of its origin. North America and Scandinavia are the world's leading exporters of pulp and paper (**Figure III-5**). Adding up these export numbers shows, that as for pulp, a relatively small part of the total paper production is exported.



(Source: PPI, 2001)

Figure III-4. Exporters of paper and pulp.

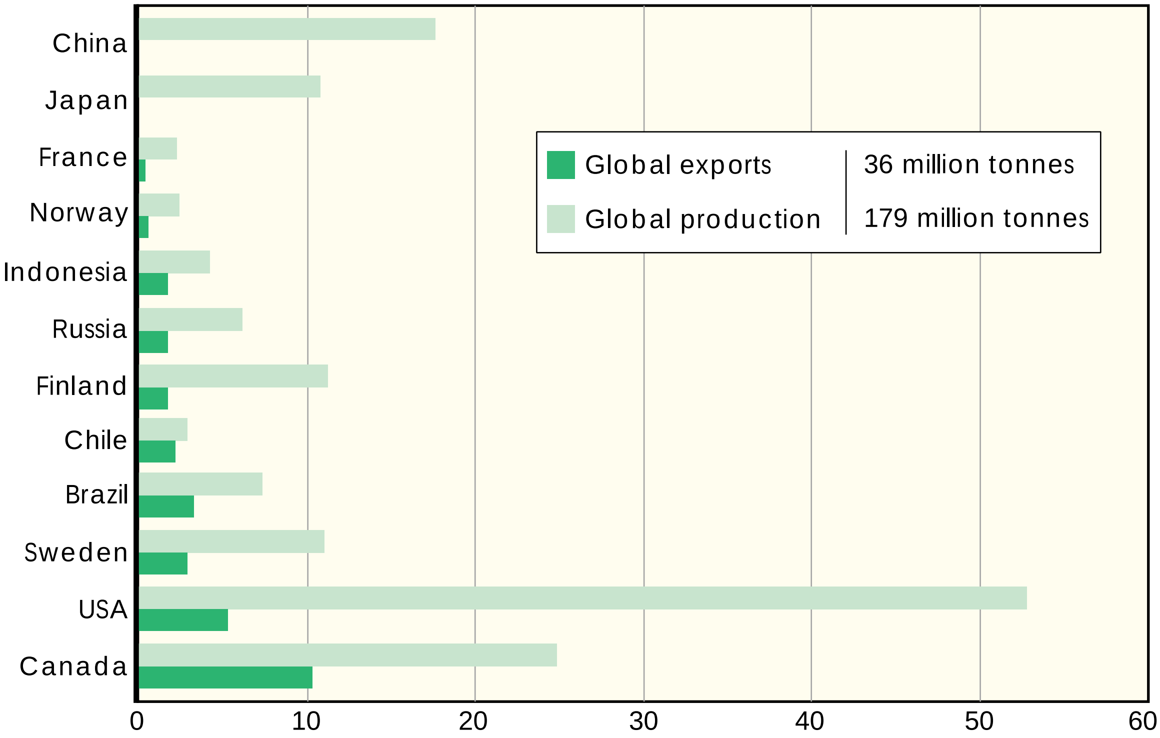


Figure III-5. Pulp production and exports in 2001.

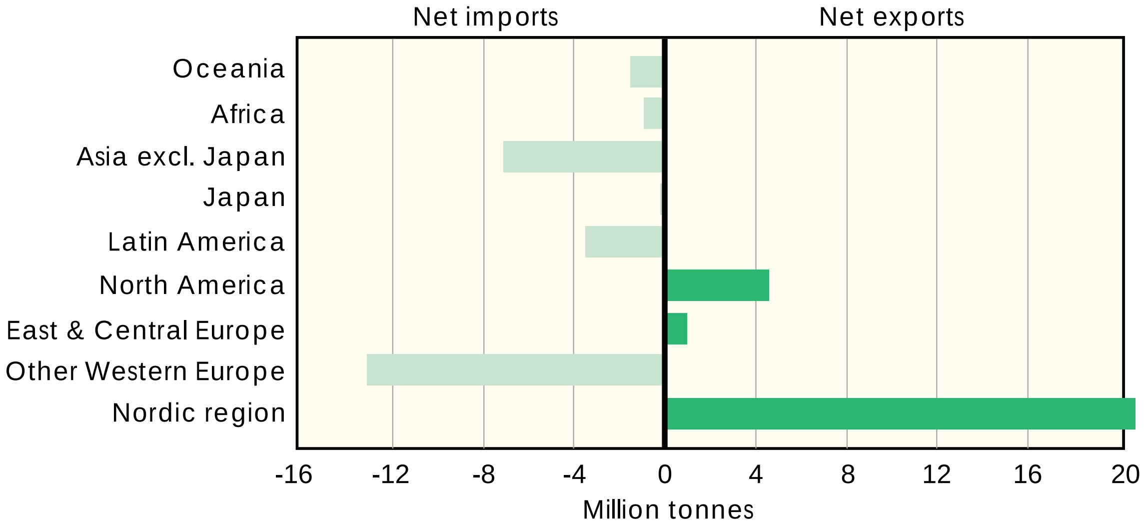
The net trade in paper between regions is shown in **Figure III-6**. A great deal of the trade occurs within these regions or with nearby regions. As an example, Sweden exports a large share of its paper to Western Europe.

Technology Description

Recycling paper is important both from the point of view of raw-material efficiency and more importantly in the short term for waste management. As an example, Sweden produces about 11 million tonnes of pulp. In 2002, its paper industry consumed 1.86 million tonnes of wastepaper. Newspapers and corrugated board met most of the wastepaper requirements and accounted for a total of 85%. Packaging material collected from households, paper from offices, and production waste from the printing industry were also used.

Newsprint mills consumed a large share of the wastepaper (45%), together with mills producing material for corrugated board (31%). In 2002, almost 1.5 million tonnes of wastepaper was collected in Sweden, mainly consisting of newspapers and corrugated board. This yields a collection ratio (volume collected as a percentage of paper consumption) of 69%. Sweden has considerable requirements for imported wastepaper, mainly newspapers and corrugated board. In 2002, imports amounted to 602,000 tonnes, corresponding to 32% of the industry's wastepaper requirements. Exports amounted to 190,000 tonnes and consisted mainly of high-grade wastepaper.

Pulp production rests on two main processes, a chemical and a thermomechanical process (TMP), each with variations. The chemical alkaline sulfate process or "Kraft" process was the industry standard until the late 1960s when TMP was developed. Most developed countries have shifted a large share of their pulp production to TMP because it produces significantly less pollution at a lower cost per tonne of pulp. TMP is also more efficient in using raw materials and less capital-intensive than the chemical process. Kraft pulp often



(Source: PPI, 2001)

Figure III-6. Net trade of paper in 2001.

needs bleaching, while TMP does not. However, the Kraft process is more suited to higher quality paper as it produces stronger fibers and it can use most types of wood, whereas the TMP pulp produces weaker paper, cannot use all raw materials, and is more energy-intensive. Today, TMP pulp amounts to about 30% of total global pulp production.

Even though the industry is energy-intensive, a paper-and-pulp mill is also a complex process industry. New, more energy-efficient technologies will be used in an existing plant only if it is undergoing a major upgrade for other reasons. Investments in the industry are large and the investment cycle is typically on the order of 30 years. Technically successful process improvements will have a barrier to being introduced in that they make present investments obsolete before they have paid off.

Technology Status

The RD&D community for the paper and pulp industry consists of the industry itself, process-engineering firms and consultants, manufacturers of different kinds of equipment, universities, and specialized (often national) research institutes, each with responsibility for different RD&D areas. Both industry and national governments normally finance RD&D programs. There is also considerable international cooperation, e.g., the International Energy Agency (IEA) program and within the European Union's R&D program.

The IEA program for energy-efficient technologies for the paper and pulp industry at present focuses mainly on two areas:

- Process integration, including tools for water management and papermaking at a low water-consumption level and the use of thermal pinch analyses.
- Gasification technologies for black liquor and biomass.

RD&D: Goals and Challenges

The challenges for the industry and therefore the driving forces for its RD&D agenda are—

- New and profitable products
- More efficient use of raw materials and chemicals, including recycling of both
- Less environmental impact through improvements of existing processes and new processes, e.g., the sulfur-free Kraft process
- Higher energy efficiency.

Sustainability in general is an underlying driving force but so is customer pressure to decrease the environmental impact of both production and the use of products. The forces are interlinked because the raw material is used for both fiber production and internal energy conversion to heat and electricity. There might also be options for external deliveries of electricity and heat through industrial backpressure generation (CHP) or liquid, solid, or gaseous biofuels. Chemicals can also be recycled. Important R&D fields are so-called "closed pulp and paper mills," process optimization including modeling and control technology.

The American Forest & Paper Association, in collaboration with the U.S. Department of Energy (DOE), published a roadmap in 1999 of R&D for the forest products industry looking ahead to 2020.[4] The forest products industry covers several other branches of the industry, including the paper and pulp industry, our main concern here. The study identified five major areas of R&D important to the industry:

- Fuel production and enhancement
  - Improved moisture reducing techniques
  - Technologies for wastes and other recyclable materials
- Fuel conversion and electricity production
  - Biomass and black liquor gasification
  - Improved understanding of the fundamentals of energy conversion techniques, especially fluidized bed, gasification, and combustion of fuels and black liquor
  - Development of technologies, e.g., fuel cells to be used in combination with gasification to enhance energy efficiency
  - Model development to allow size and plant integration optimization
  - Concept and technologies for life extension of Tomlinson furnaces.
- Manufacturing process efficiency and heat recovery
  - New technologies for recovery of low-level heat
  - New or more efficient processes of water removal prior to drying
  - Reduced variability/improved process control
- Environmental impact of energy production and utilization
  - Ash utilization options
  - Sludge utilization options
  - Improved combustion technologies
  - Alternatives to combustion of VOC gases
  - Increased efficiency and use of biomass fuels
- Wider use of renewable resources
  - Commercialization of improved biomass to chemicals technologies
  - Process integration alternatives allowing for attractive chemical production alternatives
  - Understanding of the energy efficiency in the production of paper products relative to competing products.

The paper and pulp industry has similar research needs as other industries in areas like pumps, ventilation and air conditioning, efficient lighting, and electricity transmission and distribution (for self-generation). The industry is particularly important for developing countries because the market will continue to have its highest rate of increase in those countries.

Commercialization and Deployment

Technology for industry in the developed world is highly developed and the most modern plants have high productivity, energy efficiency, and low environmental impact. Further improvements are expected as RD&D continues to deliver results. Improved technology transfer is of the utmost importance and may permit leapfrogging as the industry is being built in new regions and countries. Less pronounced but still important features of the present RD&D agenda contain process optimization and mini-plants.

An example of the direction of RD&D in the pulp and paper industry is the Swedish project, the Ecocyclic Pulp Mill (KAM),[5] financed jointly by government and industry. The program vision is for high quality paper product production with efficient use of biomass energy. The project is focused on the Kraft process and bleached pulp. The key RD&D issues are—

- Mineral balances
- Minimizing solid residues
- Reduced energy consumption
- Utilization of surplus energy
- Alternatives to the Kraft process.

Important process design areas are—

- Delignification and bleaching including alternatives to Kraft pulping
- Inorganic non-process substances in an extensively closed pulp mill
- Separation systems for nonprocess substances (chip leaching, different purge systems for the bleach plant, e.g., membranes)
- Lignin recovery from black liquor
- Solid residues and mineral balances.

Energy-relevant parts of the KAM program are energy systems and energy potential (energy use, potential for increased energy efficiency), new evaporation plant designs, energy consequences of lignin precipitation, and the use of biomass fuel surplus. Model mills with chip leaching, lignin removal, electricity generation using on black liquor, and methanol fuel production show good promise. An important conclusion of the program is that the Kraft process has no viable alternative, but it has significant potential for further development in many respects, including reduced CO_2 emissions. Estimates of timeframes for first full-scale implementation of energy-related techniques are as follows:

- Short term (1–5 years)
  - Condensing power from excess energy
  - Heat integration particularly in black liquor evaporation

- Medium term (5–10 years)
  - Sale of precipitated lignin
  - Possibly black liquor gasification with power or methanol production (uncertain)
- Long term (>10 years)
  - Black-liquor gasification with power or methanol production
  - Chemical recovery through gasification for alkaline sulfate cooking.

Risk Factors

- Technical—2: Technical risks are low, with the exception trained and experienced operations personnel in developing countries.
- Commercial—3: Competition may result in considerable risk for the industry in the developing world. On the other hand there may be substantial benefits from globalization.
- Environmental—1: The potential for vastly decreased environmental impact and the use of recycling has significant benefits for the environment
- Regulatory—4: It is not known what regulations governments will require in different countries, nor what their impact will be. The industry is highly regulated in developed countries with regard to air and water emissions and utilization of chemicals. Some nations also regulate the share of recycled paper in pulp production.

2. Iron and Steel

World steel production for 2002 was 900 million metric tonnes.[6] After a slowdown in the early 1990s, annual growth has picked up and was 2.4% for the period 1995–2000 and 3.2% for the years 2000–2002 (**Figure III-7**).

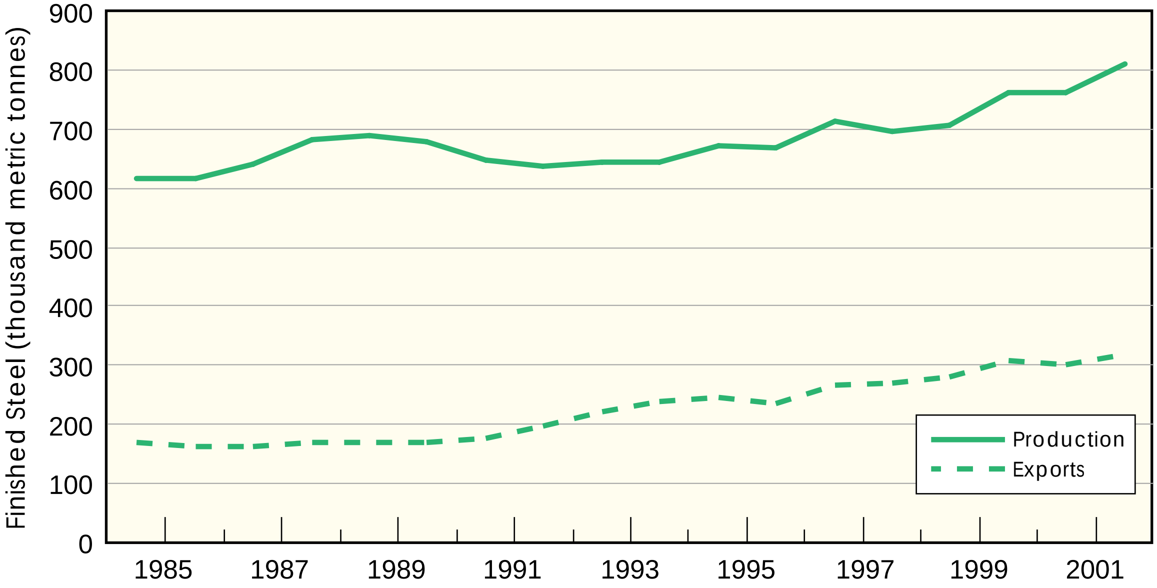


Figure III-7. Global production and trade in finished steel (International Iron and Steel Institute, 2003).

System Concepts

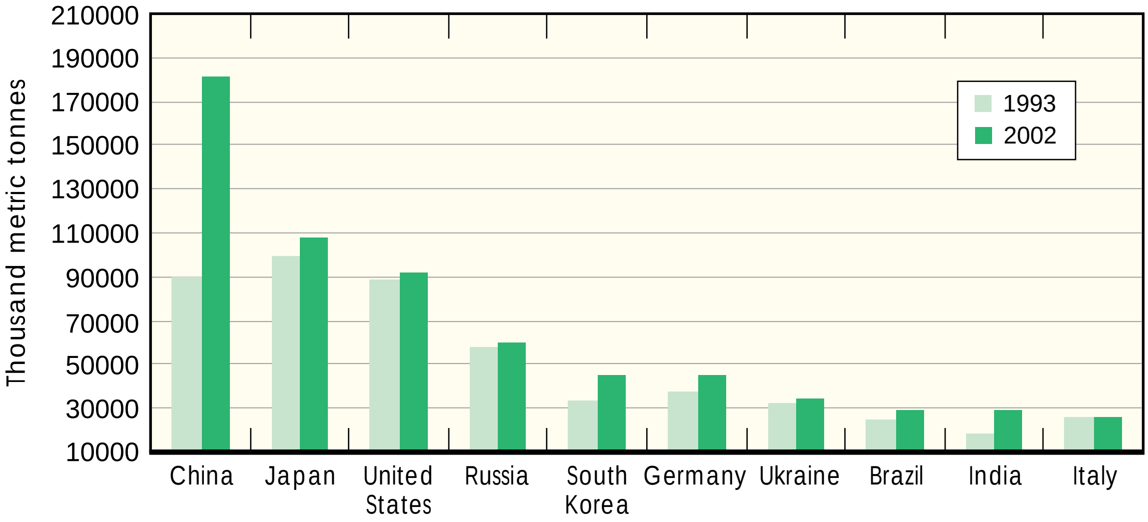
The major steel-producing countries (**Figure III-8**) are China, Japan, the United States, and Russia. Together, they account for almost 50% of world production with China alone having about 20%. From 1992 to 2002, the share of world production in Asia has increased from 35% to 43%, whereas Russia's share has decreased from 16.3% to 11.2%. The European Union's share (15 countries) has decreased from 19.9% to 17.7%. China alone has increased its share from 11.9% to 25.8% (and obviously even more dramatically in absolute terms). Japan is still the biggest exporting country with Russia in second place. Japan is also the biggest net exporter (exports minus imports). Iran, Turkey, and Mexico have rapidly increased their steel production over the last 10 years. Consumption by region is shown in **Table III-1**.

Table III-1. 2002 consumption (crude steel equivalent) by percent of world total.

China	25.8
Japan	8.8
Other Asia	15.9
European Union (15)	16.8
Other Europe	4.4
Former U.S.S.R.	3.7
NAFTA	16.0
Others	8.6

Technology Description

Productivity in the steel industry has increased in industrialized countries. Today, crude steel production in the European Union, United States, Canada, and Japan is about 600 metric tonnes per employee, as compared with about 200–250 tonnes in 1980 and 350–400 tonnes in 1990. Sweden, with a long tradition in iron-ore mining and in iron and steel manufacturing, has gone through major structural change, from bulk deliveries to high-priced niche products. High-quality iron ore is one of Sweden's basic natural resources. The steel industry accounts for 2% of the GDP and 5% of exports (2001). The entire mining and metal industry accounts for about 8% of the net exports. Steel is a component in about 70% of the export goods from all branches of the manufacturing industry. Sweden has only about 0.5% of the world's steel production but is a market leader in



(Source: International Iron and Steel Institute, 2003)

Figure III-8. Producers of crude steel.

specialty products. Sweden exports about 80% of its steel production. Japan, which is the biggest net exporter (in tons) in the world, exports 10% of its steel production.

Steel manufacturing is an energy-intensive industry. Energy costs in the Swedish steel industry are about 8% of the sales. The oil crises in the 1970s hit Sweden hard because it has no indigenous resources of oil and natural gas and very small resources of coal. However, Sweden has large hydropower resources, which have been exploited from the beginning of the 20th century. Sweden carried out a large nuclear construction program during 1970–1986. Today, hydro and nuclear power have about 50% each of Swedish electricity generation. Electricity prices have been among the lowest in the world, and electricity consumption per person is among the highest in the world.

Price jumps in oil since the 1970s, together with other world steel-market developments, caused the Swedish steel industry to carry out a major restructuring process. It has also carried out a large RD&D effort in new technologies, some of which are strongly energy-related. This means that today a large share of the Swedish sales comes from alloyed steels and various advanced steel products. Swedish crude steel production, almost 50%, is in the form of alloyed steels as compared with 10–12% in the European Union (excepting Sweden), Japan, and the United States. Swedish companies lead in the following areas:

- Seamless stainless-steel tubes (Sandvik)
- Wire and strips for heat generation (Kanthal)
- Stainless heavy plates (Outokumpu Stainless AB)
- Tooling steels (Uddeholm and Ereseel Kloster)
- Ball-bearing steel (Ovako)
- Iron powder (Höganäs).

Some of these products cost almost 100 times the market price per tonne of bulk steel. Thus, specialty steels are responsible for three-quarters of the economic product of the industry.

Swedish steel production is based on two processes: the iron-ore blast furnace process and the scrap iron (electro-steel processes). Energy consumption per tonne is considerably lower for scrap iron, about 800 kWh equivalent per tonne against about 4,300 kWh per tonne for the blast furnace process. Shares between the two vary with the business cycle. When the supply of scrap is high, the shares are about equal; when scrap becomes scarce, the share of the scrap iron process goes down to 40% or less.

A recent evaluation of energy-oriented steel R&D in Sweden shows that great progress can be made in decreasing specific energy consumption for various processes and considerable environmental improvements, in particular for CO_2 emissions.[7] If specific energy consumption from various process stages had remained at the 1987 level, energy consumption would have increased by 2.8 TWh from 1987 to 1997. In reality, energy consumption decreased by 16.8 TWh for the period 1987–1997. **Table III-2** shows a breakdown of the energy savings in different processes.

Table III-2. Energy consumption in 1997 compared with 1987 (kWh equivalent per tonne).

	1987	1997	Change
Blast furnaces	4,577	4,279	-298
Sinter plants	186	68	-118
Coke plants	1,210	1,253	+43
Oxygen plants	221	211	-10
Electric furnaces	831	741	-90
Warm rolling plants	890	729	-161
Energy sales (process gases)	290	366	+76

R&D has contributed significantly to this improvement through—

- Use of olivine pellets (iron-magnesium silicate) and high-iron-content sinters in blast furnaces
- New control systems for arc furnaces and heating furnaces
- Surface conditioning of warm materials.

Looking at the different processes as a whole, energy consumption in 1997, when compared with 1987, decreased 93% for blast furnace plants, 95% for oxygen plants, 89% for electrical furnaces, and 82% for warm rolling plants. The total energy supply in 1997 for steel production was 22.3 TWh divided between coke and coal at 12.4 TWh, coke furnace gas at 2.3 TWh, oil products at 1.7 TWh, LPG at 1.8 TWh, and electricity at 4.1 TWh. The environmental impact of steel production has decreased considerably since 1970. According to a recent publication from the Swedish business association for iron and steelmaking (Jernkontoret[8]), particle emissions have decreased 70% and emissions of lead, cadmium, copper, and zinc more than 90%. The evaluation of the R&D programs also estimated the decrease in CO_2 emissions. This depends highly on the share of blast-furnace steel with its high share of coke and coal. In the scrap iron process, about 150 kWh per tonne comes from fossil fuels and the rest from electricity, which is virtually CO_2-free (in Sweden). The evaluation estimates that actual CO_2 emissions decreased 23% compared to what they would have been with specific energy consumption remaining at the 1987 level.

Technology Status

A study by the Lawrence Berkeley National Laboratory (LBNL) in the United States on the major steelmaking countries showed a general downward trend in energy intensity between 1971 and 1994.[9] Iron and steel production is the least energy-intensive in South Korea, Germany, Japan, and France, and most energy-intensive in China. The energy intensity of steelmaking in the United States fell over 20% between 1971 and 1994. Japan, Poland, and France now show a slight increase in energy intensity in recent years. The lowest energy intensities are in the range from 20–25 GJ/tonne. Energy intensity in China is higher, but has also decreased from 60 GJ/tonne in 1990 to below 40 GJ/tonne in the middle 1990s. The study concludes that U.S. steel plants are relatively old and their production has fluctuated dramatically in the recent past. Metallurgical coal is still the primary fuel but the use of gas and electricity has been increasing. Although energy intensity and specific carbon emissions have decreased, the United States still tends to have higher energy intensities than other big steel producers. Best industry practice found in France, Germany, Japan, South Korea, and the United States is about 15 GJ/tonne.

The authors investigated over 45 specific energy-efficiency technologies applicable to blast furnaces and steel mills. The evaluation estimated energy savings, CO_2 savings, investment costs, and operation and maintenance costs for each measure. The result is a total cost-effective reduction for U.S. iron and steelmaking of 3.8 GJ/tonne, equivalent to achieving an energy savings of 18% of 1994 iron and steel energy use and 19% of 1994 iron and steel CO_2 emissions. This estimate is believed to be conservative, as it does not include all possible efficiency measures or synergistic effects of lowered costs when investing in multiple technology upgrades.

The LBNL study concluded that at least 19% of energy use in U.S. iron-and steelmaking could be saved through the introduction of currently available technology. New capabilities being installed, for example, in developing countries would be expected to utilize these technologies. In the coming decades, even newer technologies will be introduced that save even more.

RD&D: Goals and Challenges

Long-range driving forces for the industry are to get the most out of each kilogram of raw material, to use energy more efficiently, and to develop tools required to evaluate these aspects. R&D expenses as a share of operation of the Swedish steel industry are higher than in competing regions, running at 2% of turnover, as compared with the EU average of 1%, United States of 0.5%, and Japan of 1.8%. New products are to a great extent developed in collaboration with customers.

The R&D program of the Swedish Steel industry is focused on—

- High-performance steels using fewer raw materials and high-strength steels resulting in less weight in construction
- High-performance steels with longer lifetime for the final product, thus reducing the consumption of raw material and attacks of corrosion
- High-performance steels, making it possible to decrease machinery and utilize processes with higher energy efficiency.

The objectives are in line with decreased environmental impact and greater energy efficiency because—

- High-performance steels require less material consumption
- High-performance steels prolong life times on steel constructions
- High-performance steels have better energy efficiency both during the production process and in machine construction.

Some of the scientific and technical tools to accomplish this are modeling and simulation of processes (see Part III.D.9) and process control technologies (see Part II.D.8) based on improved understanding of the basic physics and the use of artificial intelligence and adaptive technologies in advanced process control.

Since 1994, 30 of the world's leading steel companies have cooperated to drastically change the role of steel in manufacturing cars (see Part III.D.4). Tests show that high-performance steels, together with new manufacturing techniques such as laser welding, can make a car 25% lighter without a decrease in performance, safety, or total economy. Companies expect an entirely new car concept to emerge from 2004 based on Advanced High-Strength Steel (AHSS).

Hardox and Weldox are new high-performance steels made by quenching. As an example, 30 years ago, the largest mobile crane with a telescopic arm could lift 50 tons. Today, the same type of crane, using the world's strongest construction steel, Weldox 1100, can lift 500 tons.

Other items on the R&D agenda include—

- Developing principles for steel construction methods for buildings.
- Utilizing waste products such as blast-furnace ashes in cement.

Commercialization and Deployment

The U.S. DOE has given a grant to a consortium of steel, metal, and microwave companies to develop a new process for steelmaking.[10] Direct steelmaking through the combination of microwave, electric arc, and exothermal heating produces molten steel directly from a transportable agglomerate consisting of finely ground iron oxide, powdered coal, and fluxing agents such as ground limestone. This technology is projected to eliminate many current steelmaking steps such as coking, sintering, blast-furnace (BF) ironmaking, and basic oxygen furnace (BOF) steelmaking. The technology is expected to—

- Save up to 25% of the energy consumed in conventional steelmaking, by replacing blast furnaces and blast oxygen furnaces with more efficient technologies
- Reduce the emissions of SO_x and NO_x
- Substantially reduce waste and emission control costs
- Greatly lower capital cost
- Considerably reduce production costs.

The technology is expected to satisfy the molten steel demands of both integrated steel mills (iron ore to finished steel in a single location) and so-called *mini-mills* (typically scrap iron feed with electric furnaces also in a single location). The project is based on the capability of microwaves to heat the agglomerate to temperatures sufficiently high for the rapid reduction of the iron oxide component (consisting of crushed and ground iron ore) by the coal. The products are then heated to steelmaking temperatures by the electric arc, assisted by the exothermic reaction of coal with oxygen. The goal of the project is to assess the utilization of this new direct steelmaking technology. Among the objectives are—

- Generating a base of technical, marketing, economic, and policy data
- Developing energy, environmental, and economic targets
- Assessing more definitively opportunities and barriers
- Defining directions for future development
- Training students.

Steelmaking based on new electro-technologies has been studied under process names like ELRED and PLASMARED, but these processes have not yet reached commercial status. A barrier to introduce new technology in an existing steelmaking plant is investments already made in blast furnaces and blast oxygen furnaces that are still highly competitive. The same type of barrier might not become as important in constructing new plants provided the technical development of the process becomes successful. From the perspective of developing countries, one aspect is the economies of scale connected with the new technology, which has import for mini-mills.

Risk Factors

- Technical—1: Proven technologies are available.
- Commercial—1: The new technologies are cost effective.
- Environmental—3: These new energy efficient technologies have concomitant benefits in reduced regional and global emissions.
- Regulatory—4: Government agencies will have to promote and allow the introduction of new technologies.

3. Aluminum Smelting and Fabrication

System Concepts

The world’s production of aluminum in 2002 was about 23 million tonnes. The U.S. share was 16%. In the United States, about 32% of annual production is for the transportation sector (ground and air). The container and packaging markets consume about 21% of production, and the building and construction industries 16%. Aluminum smelting and fabrication require a reliable electricity supply. Because power requirements are high, the aluminum industry has long had a strong motivation to reduce overall production costs by reducing the amount of electricity needed, and to make better and stronger alloys using smaller amounts of raw material. The major applications of aluminum worldwide are shown in **Figure III-9**.

North America is the largest producer of primary aluminum (**Figure III-10**). This report relies on the Aluminum Industry Technology Roadmap.[11] As a leader among regions, North America is capable of setting RD&D needs and a strategic research agenda that will propel the entire aluminum industry forward at a global level.

Technology Description

The annual electricity bill for U.S. aluminum production is about $2 billion, or about 1% of total domestic electricity sales. The large consumption results from the use of the Hall process for electrochemical reduction of anhydrous alumina. The Hall process uses a "cell" with carbon lining (the cathode) containing an electrolyte of molten cryolite (Na_3AlF_6), in which the aluminum oxide is dissolved. Carbon electrodes (the anode) are inserted into the molten electrolyte bath. The alumina is reduced to liquid aluminum metal at the cathode, and the aluminum is siphoned out of the cell. At the anode, oxygen combines with carbon from the anode to yield carbon dioxide. Approximately half a kilogram of carbon is consumed for every kilogram of aluminum produced. Based on the theoretical decomposition voltage of Al_2O_3, the energy required for Al production is less than 11 kWh/kg. However the industry average energy requirement is about 15 kWh/kg, with the most advanced cells operating at 13 kWh/kg.

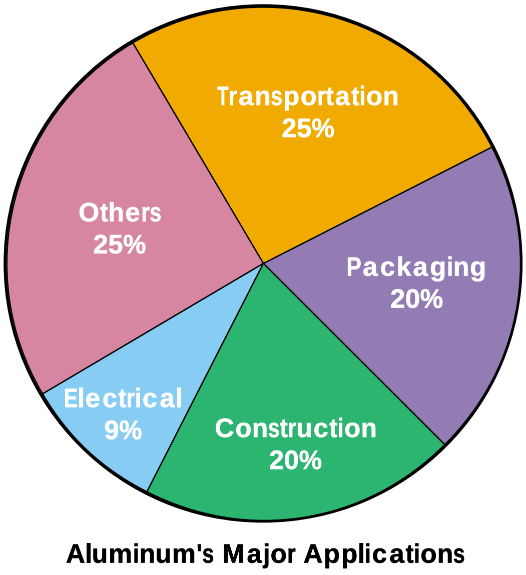


Figure III-9. End-use applications of aluminum.

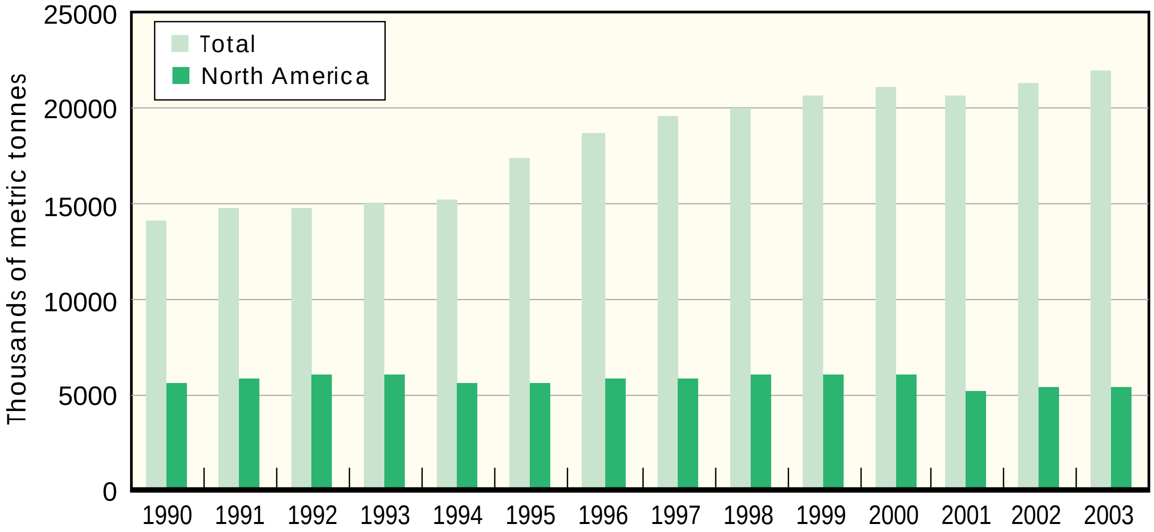


Figure III-10. Primary aluminum production as a function of time.

The high cost of producing aluminum from ore makes recycling very attractive. The energy requirement for recycling beverage cans, for example, is only about 5% of the amount needed to produce an equivalent amount of metal from the ore. The energy saved by recycling one tonne of aluminum is enough to power an average-sized house for 10 years. In 2002, about 53 billion beverage cans were recycled in the United States.[12] World aluminum production, the increasing recycle of scrap material, and total usage are shown in **Figure III-11**.

Technology Status

The Global Aluminium Sustainable Development Initiative, published by the International Aluminium Institute,[13] addresses the sustainability issues of the aluminum industry on an international scale. The report highlights common objectives that the global aluminum industry aspires to achieve:

- Reduction of perfluorocarbon (PFC) greenhouse-gas emissions per tonne of aluminum produced by 80% for the industry as a whole by 2010 vis-à-vis 1990.
- Reduction of fluoride emissions per tonne of aluminum produced for the entire industry by at least 33% by 2010 from 1990 figures. The target figure will be reviewed after 3 years.
- Reduction of the industry’s consumption of smelting energy by 10% by 2010 from 1990.
- Implementation of Management Systems for Environment (including ISO 14000 or equivalent certification) and for Health and Safety in 95% of Member plants by 2010.
- Monitoring the global performance of recycling and using the data to set voluntary targets. A global action program will be developed to encourage an increase in the volume of aluminum metal recovered form scrap.
- Supervision of annual aluminum shipments for use in the transport sector to track aluminum’s contribution in reducing greenhouse-gas emissions from road, rail, and sea transport through its light weight.

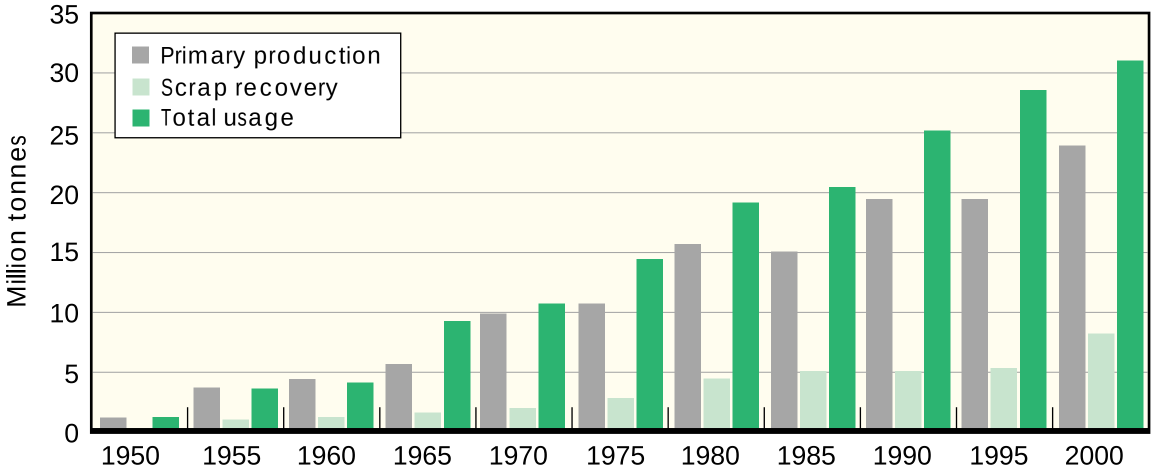


Figure III-11. World aluminum usage from 1950–1999.

RD&D: Goals and Challenges

The environmental issues associated with aluminum production fall into two major categories. The first is the need to address the high-energy requirements of the Hall process (and the Bayer process, which calcines the aluminum ores to produce the high-purity alumina required for the Hall process). Most of the electrical energy in aluminum processing comes from hydroelectric generators, so costs and emissions are relatively low. However, there is continuing pressure to reduce the costs and improve the efficiency of production. These efforts will reduce the environmental impact of production. The second issue is the emission of greenhouse gases. The oxygen removed from the alumina in the Hall process oxidizes and consumes the carbon anode. Improving the efficiency of aluminum production can substantially reduce the release of CO_2. Perfluorocarbon, a potent greenhouse gas, is also released at the anode.

The Aluminum Association and the U.S. DOE have developed a technology roadmap for the aluminum industry, updated in 2003. Among the key targets and goals are the following:

- Exceed the recycling rate of all other materials and establish the industry as a leader in sustainability. Targets include 100% recycling of aluminum by 2020, and closing the value gap between virgin and recycled materials.
- Make a positive net impact on the environment over the life cycle of aluminum products.
- Produce zero-net emissions of greenhouse gases on a life-cycle basis.
- Meet or exceed a target of 11 kWh/kg for smelting and achieve other energy efficiency targets established by the industry. This goal includes defining the next generation of (non-Bayer and non-Hall-Heroult) energy efficient processes.
- Generate a net energy advantage over the life cycle of aluminum products. Specific targets are reducing the cost of metal production and products by 25% by 2020, and reducing energy use in melting by 25% by 2020, and reducing carbon consumption to 0.4 kg per kg of aluminum.

The roadmap also includes a summary of the highest-priority technology development needs:

- Inert or non-consumable anodes to take the place of the consumable carbon electrodes described earlier can yield benefits in many areas. Costs can be reduced, productivity improved, energy use reduced, and greenhouse gases eliminated (both CO_2 and perfluorocarbons). The roadmap defines a set of performance characteristics that an inert anode must have, including electrochemical behavior, electrical conductivity, erosion rate, mechanical properties, oxidation resistance, and economic benefits. Currently, no materials are available that meet all or even most of these requirements. However, the roadmap defines the critical steps in the technology development process, from defining the chemical and thermodynamic underpinnings of a successful process to bench top studies of candidate technologies, to pilot and full-scale demonstrations.

- Knowledge gaps in aluminum processing range from the need for fundamental information on solidification, to first-principle predictions of the relationships between metal quality and economics, to the optimization of manufacturing processes of scrap-tolerant alloys. Research opportunities include the development of predictive models for all aspects of aluminum processing, including melting, solidification, and recycling. A second high-priority research topic is the development of strip and slab casting technologies to produce a more uniform product with better surface finish and reduced segregation. A third research topic is the integration of a variety of concepts to define the melting and casting plant of the future.

Two critical themes run through the priorities. The first is the growing importance of modeling as a tool to evaluate new technologies. The second is the need for improved sensors as part of an overall effort to improve monitoring and control of the aluminum production and fabrication processes.

Commercialization and Deployment

The Aluminum Industry Technology Roadmap 2003 focuses mainly on three areas: Products and Markets, Sustainability, and Energy and Resources. It defines industry-wide performance targets for tracking progress and achievement of strategic goals involving technical solutions in these areas. Detailed sector-specific targets, technological barriers, R&D priorities are presented in the roadmap. Estimated timelines are also provided. The roadmap categorizes R&D needs based on different processes:

- Primary production
- Melting, solidification, and recycling
- Fabrication
- Alloy development and finished products.

The strategic goals are aligned with industry-wide performance targets to ensure the accomplishment of the goals in a timely fashion. The strategic goals are envisioned in order to establish the aluminum industry as a leader in the global economy. The sustainability goal is to exceed the recycling rate of all other materials and establish itself as the leader in sustainability. The aluminum industry aims to generate a positive impact on the environment over the life cycle of products. It also wants to produce zero emissions of greenhouse gases on a life-cycle basis. To achieve sustainability goals, the industry has defined certain performance targets:

- Recycling 100% of aluminum by 2020
- Closing the value gap between new and recycled materials so as to optimize the value of recycled products
- Using established life-cycle scorekeeper system across all industries to assess progress
- Produce zero harmful emissions by 2020.

The cost of electricity is such a dominant factor in aluminum smelting that it surpasses transportation costs of both the ore and the finished product. This point is illustrated by Alcoa's project to build an aluminum smelter in Iceland, thousand of kilometers away from ore deposits in South America and Australia. The government of Iceland has ratified Alcoa's proposal in eastern Iceland and construction is underway. Fjardaal, translated as "aluminum of the fjords," is expected to cost $1.1 billion over four years. Scheduled to completed in 2007, the smelter will have an annual capacity of 322,000 metric tonnes.

The primary aluminum production facility will be supported by the construction of a 500-MW Karahnjukar Power Station by the national power company. The Fjardabyggd Harbor Fund will build a harbor facility at Mjoeyri to receive bauxite shipments. The plant if a hydroelectric design, consisting of a 190-meter-high, 730-meter-wide main dam, two smaller saddle dams, and headrace tunnels to be paid for by Landsvikjun, the national power company. Once completed, the Fjardaal project will represent one of the largest private investments in Iceland.

The project is not without detractors. Environmental and other groups have criticized the project on economic, environmental, and long-term sustainability grounds.[14] Among the concerns are—

- Emissions of greenhouse gases, although the project is reported to be one of the cleanest in the world;
- Emissions of SO_2, a byproduct of the aluminum smelting process;
- Local environmental issues, such as the turbidity of water in the reservoir and affected rivers and lakes;
- Blowing dust from silt exposed when the reservoir is low;
- Eventual filling of the reservoir with silt.

These issues are typical of what can be expected in licensing of all new power projects, regardless of the plant's design and fuel choice. The power industry, regulators, other government agencies, and all stakeholders have to address concerns of the general public as well as environmental groups and intervenors, about the total lifecycle costs of the power system and the end-uses of electricity.

The benefits of R&D in this end-use sector are greatly decreased energy use in what was a very energy-intensive industry. The cost of RD&D in the future, while difficult to quantify, would seem for the most part to be paid for in increased sustainability of the basic resource through increased use of scrap aluminum and decreased energy intensity.

Risk Factors

- Technical—2: Many of the technologies required are either in place or far along the development path.
- Commercial—4: Competition from other products could impact commercial success

- Environmental—1: The benefits of efficient use of materials and energy seem to far outweigh the risks.
- Regulatory—3: Always difficult to ascertain but the industry seems to be vigorously pursuing markets and regulations in tandem.

4. Cement

In 1999, the U.S. cement industry consumed 560 PJ (531 TBTU) of final energy, which was about 2% of total U.S. manufacturing energy use and emitted 22.6 million tonnes of carbon (including emissions from power generation), or about 5% of total U.S. manufacturing carbon emissions. Specific energy consumption was on average 5.6 GJ/tonne in terms of primary energy. Today, fuels for cement production in the United States are largely coal and coke, whereas in the 1970s, the major fuel was natural gas. Waste fuels have increased since the 1980s and their share of primary energy was about 11% in 1999. Electricity is consumed mainly in raw materials preparation.[15]

System Concepts

Between 1970 and 1997, primary physical energy intensity for cement production in the U.S. dropped 30% from 7.9 GJ/tonne to 5.6 GJ/tonne and carbon emissions dropped 25% from 0.16 to 0.12 tonnes per tonne of cement produced. The cited reports investigate about 40 technologies and measures for energy and CO_2 savings, investment, operation, and maintenance costs. The authors of Reference 13 have constructed an energy conservation supply curve for the U.S. cement industry and find a total cost-effective reduction of 0.6 GJ/tonne of cement consisting of measures with a simple payback time of 3 years or less. This is equivalent to 11% of 1994 energy use for cement-making in the United States and savings of 5% of total CO_2 emissions.

The Asian Institute of Technology has carried out a study of energy environment and climate change issues in the Philippines funded by the Swedish International Development Agency (SIDA) and using 1994 data. Comments about the cement industry are fairly harsh. “There are three types of processes employed by the industry, wet, semi-dry, and dry. The technologies employed in the Philippines are outdated, resulting in high fuel and electricity consumption. The principal fuels used are coal, coke, and fuel oil. There is tremendous scope for improving the efficiency of energy use in the cement industry relieving the burden of energy cost and contributing significantly to lower production costs and competitiveness. There is a need for high efficiency dust collectors to be installed to remove the large amounts of particles discharged into the atmosphere.”

The economy of the Philippines is now approaching a growth rate of 6% per year with industrial growth at around 5%. A number of constraints exist for industry. There is no longer a shortage of electricity, but the electricity supply is unreliable. Voltage-sensitive, cement-making equipment, such as precipitators, has difficulty performing on the national grid. Inconsistent and inferior quality fossil fuel containing a high percentage of sulfur has also caused corrosion problems in boilers, kilns, and furnaces. Prospects for improvements in energy efficiency in the Philippine cement industry are large not only because of its large share of the country's energy consumption but also because the sector consists of a manageable number of energy-consuming facilities of some size as compared to other sectors. Technologies to improve the efficiency at the end-user level have been identified and to some extent are already being adopted by industry.

Technology Description

The U.S. cement industry is made up of clinker plants and cement production plants. Clinker (oxides of the raw ingredients) is produced through a controlled, high-temperature kiln burn with a wet or a dry process. Cement plants grind clinker and add a variety of additives to produce cement. Clinker production in the United States increased from 67 million tonnes in 1970 to 74 million tonnes in 1997, with an average growth of 0.4% annually with dips in the late 1970s and early 1980s. Clinker production with the dry process has increased more rapidly than with the wet process. The dry process now accounts for 72% and the wet process for 26% of clinker production. Between 1970 and 1997, U.S. cement production increased by 0.7% annually. Materials consumption increased at an average of 0.5% per year between 1970 and 1997 (from 115 million tonnes to 133 million tonnes). The difference in growth rate for clinker production, cement production, and materials consumption may be due to increased use of additives and increases in clinker imports. The number of U.S. plants has decreased between 1970 and 1997, but the average plant size had increased.

Technology Status

Following are some examples of the 40 technologies investigated in the U.S. reports:

- Raw material preparations
  - Efficient transport systems
  - Raw meal blending systems
  - Conversion to closed circuit wash mill
  - High-efficiency roller mills (dry cement)
  - High-efficiency classifiers
- Clinker production
  - Combustion system improvements
  - Kiln shell heat-loss reduction
  - Use of waste fuels
  - Dry process
  - Heat recovery for power generation
  - Low-pressure drop cyclones for suspension pre-heaters

- Finish Grinding
  - Improved grinding media (ball mills)
  - High-pressure roller press
- General measures
  - Preventive maintenance
  - Energy management and process control. Fuzzy logic systems.
  - Reduced kiln dust wasting
  - High-efficiency motors
  - Efficient fans with variable-speed drives
- Product changes
  - Blended cements
  - Reducing the concentration of C_3S in cements
- Advanced technologies
  - Fluidized bed kiln
  - Advanced grinding technologies based on ultrasound, laser, thermal shock, electric shock, or cryogenics.
  - Mineral polymers

RD&D: Goals and Challenges

Further improvements can be made through changes in product mix. If production of blended cement increases in the United States, as is common in many other parts of the world, the energy-savings potential would increase to 1.1 GJ/tonne cement or 18% of total energy use and carbon dioxide emissions would be reduced by 16%. Thus, blended cement production could be a key to a successful strategy for energy efficiency improvement and carbon dioxide reduction in the U.S. cement industry. In the 1999 LBNL report, 30 technologies were ranked for cost-effectiveness. Twelve or thirteen of them were economic with simple payback times of three years or less. The accumulated savings for these measures were about 0.7 GJ/tonne or 11% of primary energy use in the cement industry for 1994. Looking at electricity-based technologies, high-efficiency motors had a calculated payback of 0.9 years and variable speed drives 2.4 years. Other than that, the measures related to raw materials preparation, where most of the electricity is consumed generally had very long payback times. The technical potential for savings for all the 30 technologies was about 180 PJ or 40% of primary cement industry energy use in 1994.

Commercialization and Deployment

The developing world can, in most cases, adopt the most modern and energy-efficient cement production technologies for new plants, such as fluidized bed kilns, optimized grinding including recovery of waste heat, and the use of mineral polymers to immobilize wastes. In the developed world, careful economic analysis will determine when switches to more modern technologies are made. These analyses, as well as those that are done in the developing world for new systems, must be careful to evaluate life-time projections in terms of energy consumption for the systems as well as the expected completion of the RD&D cycle for new technologies.

The benefits of new technologies in the cement industry to society and economies are enormous, both from the standpoint of energy efficiency and carbon dioxide and other pollutant reduction. Much of the technology to achieve these gains already exists, so the RD&D costs are minimal. Adopting current advanced technology without the need for extensive RD&D can have high gains.

Risk Factors

- Technical—3: See above comments on state of the technology.
- Commercial—2: Most of the technologies are proven and cost little to implement and should help successfully commercialize the product.
- Environmental—2: The benefits from reduced regional and global air pollution far outweigh the costs.
- Regulatory—1: Although there are always unforeseen government regulation problems when switching from the established way of doing things, there should be ample incentive for introducing these new technologies.

5. Chemicals

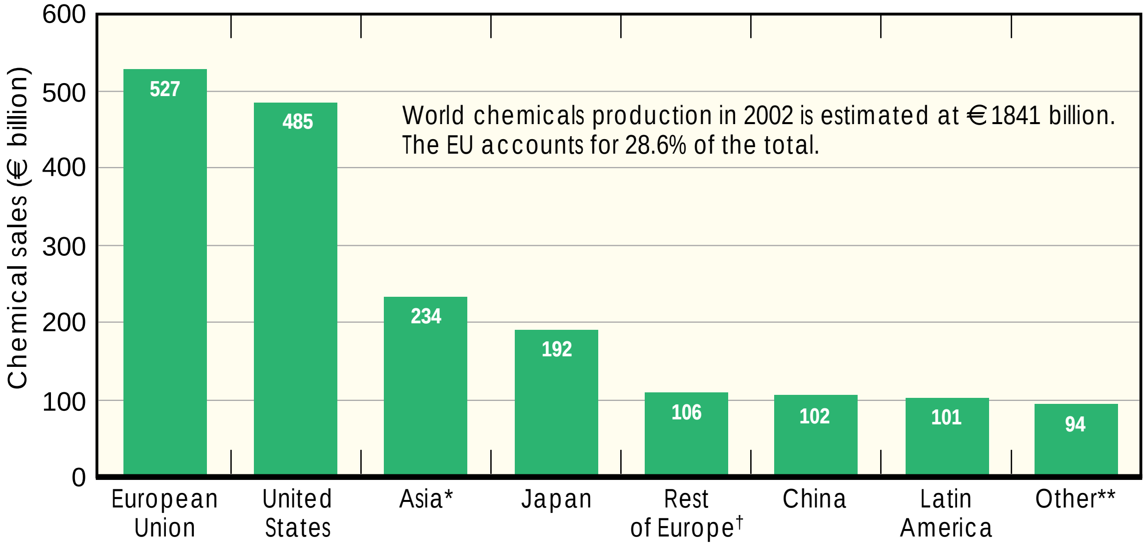
System Concepts

The chemical industry accounts for approximately 7% of GWP and 9% of global trade.[16] It consists of many branches, and countries do not often lump all the same branches in their national industrial statistics. The most important branches are Base Chemicals, Fertilizers and Base Plastics, Paints, and Explosives. Some countries also classify Pharmaceuticals, Rubber, Plastics, and Petroleum Refineries as being within the chemical industry. The European Council for the Chemical Industry gives a picture for world production and trade and the regional distribution of trade in 2002 (**Figures III-12** and **III-13**).[17] The United States is the largest producing country and is slightly behind the overall European Union.

Technology Description

The chemical industry is among the most energy-intensive industries, and there are many opportunities to apply new technologies to reduce capital and energy operating costs to improve both economic and environmental performance. Many of the emerging technologies consist of improved processes that work at lower temperatures to reduce energy requirements, or make more effective use of catalysts. An example of improved catalysts is the development of nano-scale substrates based on molybdenum and tungsten carbides.

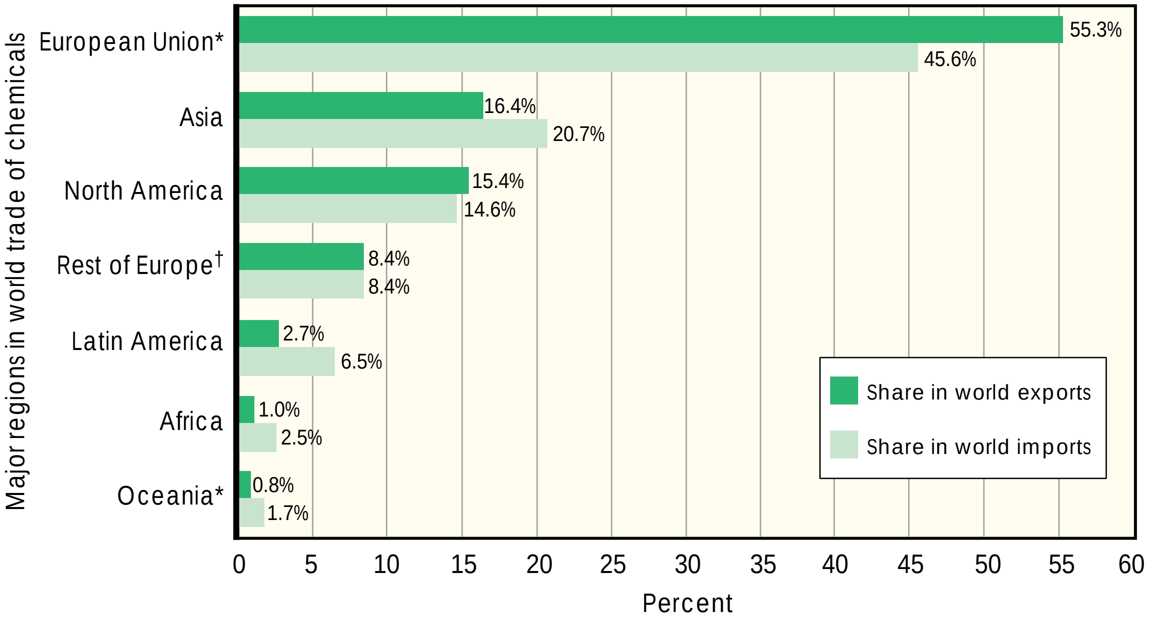
These catalysts are supported on a substrate of carbon nanotubes and nanorods. They maintain thermal stability and high surface area, even under severe operating conditions. These new catalysts offer the performance of platinum without its high cost.[18] Projected energy savings in the United States are 45 PJ per year by 2020.



* Excluding Japan and China
† Switzerland, Norway, Central and Eastern Europe, and Turkey
** Including Canada, Mexico, and Oceania

(Source: cefic)

Figure III-12. Geographic breakdown of world chemical sales.



Source: cefic
* Estimated
† Rest of Europe: Other Western Europe + C&EE/Baltic States/CIS

Figure III-13. Regional share of world chemical trade.

Technology Status

According to the LBNL report on the U.S. Chemical Industry (see Reference 16), the U.S. chemical industry is responsible for about 11% of U.S. industrial value-added production, consumes about 20% of industrial energy (1994), and contributes in similar proportions to U.S. greenhouse-gas emissions. It is the largest consumer of electricity in the U.S. manufacturing sector. According to the American Electronics Association, the annual consumption in 1999 was 157 TWh followed by primary metal manufacturing at 130 TWh, paper manufacturing at 70 TWh, and food manufacturing at 61 Twh.[19] Total electricity consumption for manufacturing in 1999 was 829 TWh.

The LBNL study (see Reference 16) cites the largest energy consumers in terms of fuels in the U.S. chemical industry as—

- Ethylene production (520 PJ annually in fuels).
- Nitrogenous fertilizers (268 PJ of fuels excluding feedstock) and 368 PJ of natural gas as feedstock.
- Chlorine and caustic soda. Chlorine is produced through electrolysis. Total annual electricity use is 173 PJ (48 TWh or about one-third of total electricity use in the industry). Total primary energy use is estimated at 526 PJ excluding credits for hydrogen exports.

Ethylene Production. The United States is the largest producer in the world of ethylene with 28% of world-installed capacity. Between 1974 and 1994, ethylene production grew at 3% annually. The single most energy-intensive process in the petrochemical industry is steam cracking of hydrocarbons to produce ethylene, propylene, butadiene, and aromatics. In 1990, world consumption was 1 EJ excluding feedstock energy consumption, and world production of ethylene was 50 million tonnes. In 1997, world production had increased to 70 million tonnes. In recent years, global capacity for ethylene production has outgrown ethylene demand. In spite of this over-capacity, global ethylene production capacity is expected to grow from 89 million tonnes in 1997 to 103 million tonnes in 2020. The largest increases are expected in East Asia followed by the United States (about 7 million tonnes). Estimates of the ages of U.S. ethylene production plants vary, but a considerable share is older than 10 or 20 years. Some of the older, considerably less efficient plants have been modernized. It has been estimated that the difference in energy efficiency between plants built in the early seventies and the early nineties is on average 40% worldwide (see Reference 16).

EPRI has reported on promising technologies for ethylene production in the long term (see Reference 18). One example is the development of oxidative cracking of ethane to produce ethylene. Ethylene production is extremely energy-intensive and is now generated from ethane in a steam cracker at high temperatures. The new technology eliminates the formation of NO_x, reduces CO_2 production by a factor of 10, and in the United States, it alone has the potential for energy savings of 10–15 PJ per year by 2020. This approach may have competition from microwave synthesis, which selectively breaks the key chemical bonds in ethane. This technology offers a large performance improvement over conventional technology, and nearly eliminates the toxic byproduct stream. While this technology offers a substantial performance advantage, oxidative cracking is expected to be more familiar to workers in chemical plants and may therefore be the process of choice.

Nitrogenous Fertilizers and Ammonia. The nitrogen fertilizer industry is a large energy consumer. Global production capacity is about 100 million tonnes of nitrogen with an estimated energy consumption of 1% of global primary energy use. The production of ammonia is the most energy-intensive production step in the manufacture of fertilizers. In the United States, ammonia production is 16.3 million tonnes and about 80% of that goes into fertilizer production. The world fertilizer market grows slowly, growth mainly arising in developing countries.

The main production processes for ammonia in the United States are steam reforming of natural gas and partial oxidation of oil residues with hydrogen production as an intermediate production step. Ammonia production requires typically between 28 and 40 GJ/tonne (LHV including feed stock). The specific energy consumption for modern partial oxidation units is 30 GJ/tonne, according to LURGI in 1986.[20] The theoretical minimum energy consumption for ammonia manufacture through steam reforming is approximately 21.6 GJ /tonne (HHV) ammonia. Ammonia is used directly as fertilizer, but most of it is converted to other products before use such as urea, ammonium nitrate, and ammonium sulfate.

Chlorine Manufacture. The United States is also the largest manufacturer of chlorine. The global chlorine industry is growing, although at a slower pace than earlier, one reason being environmental concerns about the use and transport of chlorine in industrial processes. Chlorine is produced by electrolysis of brine, requiring 25–40 GJ/tonne, depending on the state of the equipment. Sodium hydroxide is produced at the same time. About half of the energy is used to break chemical bonds and goes into the product, whereas the other half goes into heat which can often be recycled. The European Integrated Pollution Prevention and Control Bureau publishes information on the best available technologies.[21] In chlorine production, the most effective technology is the membrane electrolytic cell. That technology is in its third generation and still in development.

In Sweden, 70% of the production in the chemical industry goes to export and contributed to 11% of total exports in 2002.[22] Production growth in recent years has been highest in the pharmaceutical industry, which alone is responsible for 5.5% of total exports. Employment amounted to 8.6% of the total Swedish workforce. Specialization mergers and globalization have been rapid in the industry both in Sweden and other countries. In principle, there is now only one supplier in Sweden for each base chemical produced in large volumes. Chemical plants are highly automated and designed for production of one or a few bulk chemicals.

Historically, there has been a strong link between the chemical and pulp and paper industries in Sweden. There are often industrial groups where the chemical side of the business supplied the pulp and paper side with chemicals. Waste products from the pulp and paper side in turn supply the raw materials for the chemical side. A major product was chlorine for bleaching. For environmental reasons, the pulp and paper industry subsequently changed to chlorine oxide, hydrogen peroxide, oxygen, ozone, and peroxyacaetic acid in various combinations, depending on the type of wood and type of process, for bleaching. Chlorine oxide is produced from sodium chlorate. The bonds between the two industries have decreased, and in 1990 for example, the major pulp and paper industry in Sweden, Stora Enso, sold its chemical division. Nevertheless, chlorine is still an important synthesis material in the pharmaceutical industry.

The industry in general and the pharmaceutical industry in particular are RD&D-intensive. No other branch of Swedish industry employs as many graduate scientists. RD&D staff constitutes about 17% of the total employment of the industry. RD&D expenditures amount to 19% of total Swedish RD&D expenditures. Again, the pharmaceutical industry stands out, being responsible for about 80% of the total RD&D expenditures in the chemical industry. Its RD&D expenditures amounted to about 20% of its sales as compared to an average of 4.7% for the total Swedish industry. The chemical industry is a key branch in helping to improve the environment. It is pursuing solutions to its own environmental emissions, and it provides means for other branches of industry to do so. As an example, between 1995 and 2000, the Swedish chemical industry decreased its emissions of nitrogen oxides and sulfuric oxides by 30–35%. More than 90% of the companies have environmental management systems in place (ISO 14001 and/or EMAS). More than 75% offer their customers training in the safe handling of their products. Examples of chemical products assisting other industries in the solution of their environmental problems include water treatment chemicals, catalysts for car exhausts, and adsorbent materials (zeolites) for the treatment of air pollution.

In Swedish refineries, energy intensity has decreased by about half from 1976 to 2001. In addition, part of the waste heat is used as district heat. These gains have been diminished to some extent by the additional energy required to produce lighter and more specialized liquid fuels.

RD&D: Goals and Challenges

The U.S. DOE program, Industries of the Future, aims to increase the energy efficiencies of energy-intensive industries.[23] Some examples of areas for RD&D in the chemical industry are—

- Separation technology to more efficiently separate and refine chemicals.
- Process technologies to significantly improve chemical reactions and product yields in order to increase energy efficiency in key chemical products by more than 30%.
- New alloys for ethylene production.
- A chemical industry project (Vision 2020) to develop innovative energy supply systems to save 200 PJ (about 5 Mtoe) per year by 2020.

Commercialization and Deployment

Many of the described technologies have already had an impact in the marketplace. Catalytic processes are responsible for about 75% of chemical and petroleum products by value (see Reference 1). These and other technologies are readily accepted by industries anxious to be as competitive as possible. Capital expenditures are the main impediment to rapid acceptance of these technologies by industry.

Risk Factors

- Technical—4: There are still many advances to be made, especially in applying radical new technologies to these industries.
- Commercial—5: The main question is the degree to which capital investments in plant change can be undertaken.
- Environmental—3: There should be an overall sustainable impact due to more efficient use of energy and other resources.
- Regulatory—4: As with the cement industry, it is difficult to calculate the role that government regulators will play.

6. Service Industries

Service industries are broad and diverse and are the largest component of economic activity in many developed countries. Similar development should be expected in emerging economies in the developing world. Service industries are composed of such diverse businesses as banking, finances, real estate and insurance, education, health care and social services, wholesale and retail trading, restaurant and hotels, transport and communication, consulting and personal services in different fields. National defense is also considered a service industry. Energy is not one of the principal expenditures in most service industries. However, because the overall level of activity is so large, more efficient equipment can make a large contribution to overall levels of profit and to reduced energy use.

In developed countries, service industries constitute a large share of the GDP. As an example, in Sweden service is responsible for about 70% of the GDP, whereas non-service industries are responsible for about 25% and agriculture and forestry for about 3%. The role of service is even larger in terms of percent of total employment. In Sweden, in 2001, private and public services were responsible for close to 80% of total employment, whereas conventional industry was responsible for 18% and agriculture and forestry 2%. (It should be kept in mind that state-owned industry such as the power industry in many countries is still accounted for under “Industry” in national statistics). This development has been very rapid. Going back to 1965, conventional industry was responsible for 30% of the employment in Sweden against 58% in public and private services and 12% in agriculture and forestry.

Behind the increases of the service sector lie a host of factors such as—

- The volume of existing services has increased in fields like health and child care and care for the elderly. (The aging population to date affects mostly developed countries.)
- New areas of services have emerged and play increasingly important roles. Fast food is an obvious example of a truly global industry. Other examples can be found in the entertainment industry (and especially the music industry, which for some countries is a rather important exporter).
- Consulting services have increased in scope and volume, e.g., in information technology.
- Outsourcing has increased. Industrial companies are buying services for things like economics, accounting, and personnel recruitment where it used to have these functions in house.

Conventional industry is maintaining its share of GDP but decreasing its share of employment, due to productivity development being more rapid in industry than in services. In Sweden, the service sector is typically divided into—

- Knowledge-based services (communications, finance, insurance, computer consulting etc.)
- Capital-intensive services (transport, real estate management)
- Labor-intensive service (wholesale and retail trading, hotel and restaurants, personal services).

The largest increase in service production in Sweden over the past 20 years has been in the knowledge-intensive industries.

The largest share of work in the service industries consists of office work using computers, copiers, communication equipment, and other appliances. There are also energy needs for lighting, indoor climate (heating cooling etc.) of the same type as in the Buildings sector (see Part III.B). Food-handling in stores and restaurants has fairly large energy requirements for storage. Energy requirements of the service sector are not easily accessible (if at all) from energy statistics, although one should be able to make reasonable estimates by beginning with specific needs per office worker. The relationship between development and energy efficiency of computers and office equipment is illustrated in **Figure III-14**.

LBNL has analyzed high-tech energy demand and concluded—

- Office and network equipment comprise only 2% of U.S. electricity.
- By including telecommunications equipment and energy to produce office equipment, demand share rises to only 3%.

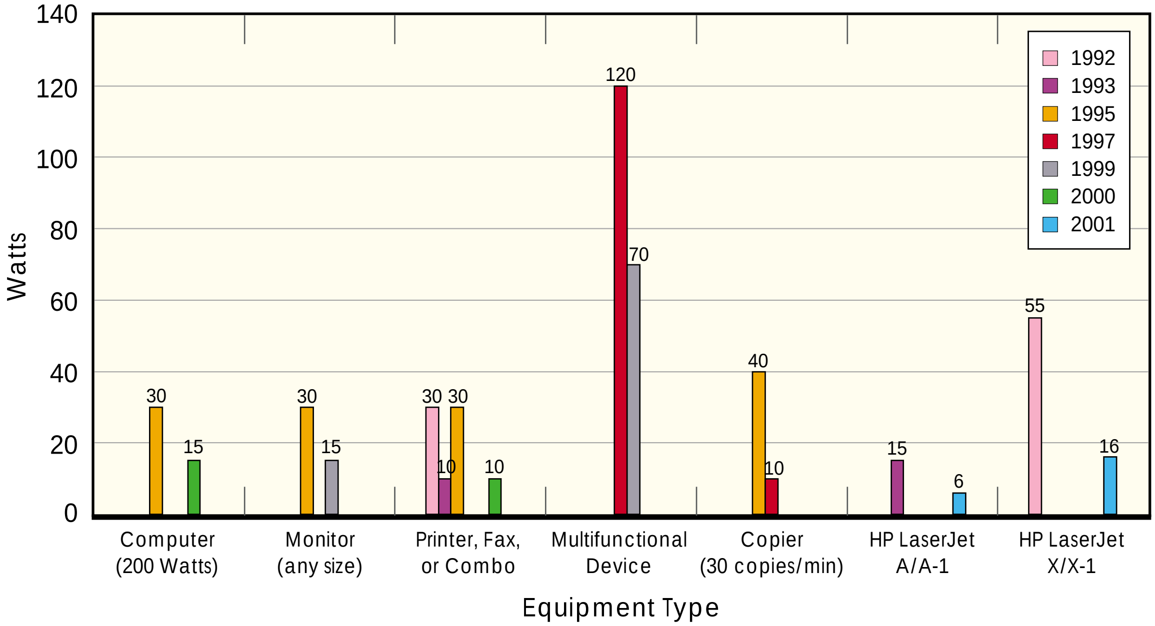


Figure III-14. Efficiency as a function of product development [Source: American Electronics Association, Electronic Industries Alliance (EIA), and Information Technology Industry Council (ITI), 2002].

Information and control technology (see Part III.D.7 and D.8) for energy management should have a large potential impact in most service industries, as it would have on the Buildings sector in general. There might be other types of effects of information technology on energy requirements because it may influence the way logistics and distribution of storage along the distribution chain is organized in food store chains, to mention one example. Today, many workers in service work share their working hours while traveling between office, home, airports, and trains and buses, meaning that their energy consumption is not easily accounted for in statistics. Total energy consumption will remain virtually the same, but it will differ in distribution in time and geography. This may have some effect on load distribution over time, and it will also increase power-quality requirements in private homes.

RD&D: Goals and Challenges

The knowledge-based economy of the future will require a “smart power” delivery system that links information technology with energy delivery. The concept of a smart power delivery system includes automated capabilities to recognize problems, find solutions and optimize the performance of the power-delivery system. The basic tools include advanced sensors, data processing and pattern recognition software, and solid-state power-flow controllers to reduce congestion, react in “real-time” to disturbances, and redirect the flow of power as needed. There are three primary objectives:

- **Optimize the overall performance and resilience of the system.** An array of sensors will monitor the electrical characteristics of the system (voltage, current, frequency, harmonics, etc.) as well as the condition of critical components, such as transformers, feeders, circuit breakers, etc. The system will constantly fine-tune itself to an optimal state, while constantly monitoring potential problems that could disturb the system. When a potential problem is detected and identified, its severity and the resulting consequences are assessed. Various corrective actions are then identified, and computer simulations study the effectiveness of each action. The operator can then effectively implement corrective action by taking advantage of the grid's many automated control features.

- **Instantly respond to disturbances to minimize impact.** When an unanticipated disturbance does take place in the system, it can be quickly detected and identified. An intelligent "islanding" or sectionalizing scheme, for example, can be activated instantaneously to separate the system into self-sustaining parts to maintain electricity supply for consumers according to specified priorities, and to prevent blackouts from propagating.
- **Restore the system after a disturbance.** Following the system's reaction to a major disturbance, actions are taken to move the system toward a stable, operating regime. To do so, the state and topology of the system need to be monitored and assessed in real time, allowing alternative corrective actions to be identified and the effectiveness of each determined by look-ahead computer simulations. The most effective actions are then implemented automatically. When a stable operating state is achieved, the system again starts to self-optimize.

Additional discussion of the smart electricity grid of the future is provided in Part III.D.2.

7. Summary

This section emphasizes the most energy-intensive industries because they are responsible for the majority of global energy consumption by industry. Most energy-intensive industries implement complex processes having long economic lifetimes and requiring large capital investments. Process changes in such industries are rarely done for energy efficiency alone. Therefore, even though energy costs are important, new energy technologies for these industries only come into play either when a major capital change is done for reasons such as market changes or when new plants are constructed. One consequence is that newly industrialized countries often have more modern and energy-efficient plants than traditional production countries. The steel industry in South Korea has far lower energy intensity than the U.S. steel industry for example. The emphasis on developing countries leapfrogging developed countries rests on such observations.

In developed countries, energy intensities in all the industries we have studied have decreased over the past 20 or so years, albeit at different rates. In some instances, for example in ammonia production, the technology is approaching thermodynamic limits (i.e., waste is minimized). At the same time, productivity has increased in lower person-hours per tonne of steel produced. In most of the industries reported here, world production is considerably larger than world trade, meaning that most of the production is consumed locally and local conditions determine the RD&D investment climate. A case in point is the cement industry. There are exceptions such as the Swedish iron and steel or paper and pulp industries whose exports are larger than national consumption. In many instances, there is currently rapid movement in production toward Asia. The large increase in steel production and consumption in China during the past 10 years is a case in point. More generally, globalization is a strong trend in many of the energy-intensive industries. Global industries move production capacity geographically to be near markets but also where economic conditions for production are most favorable.

Technologies for the industries described cover a vast spectrum, some specific to each industry and others common to almost all (e.g., pumping, ventilation, and lighting). Some important driving forces and areas for technology development are—

- New and profitable products;
- Process integration including heat recovery and co-generation of electricity;
- Efficient use of raw materials including recycling, energy efficiency, and decreased emissions contributing to sustainable development;
- Decreasing environmental impact of both production processes and product use;
- Several new electro-technologies have been identified that show promise for the future. Examples are steelmaking with microwaves and ethylene production.

There is also ample scope for improvement in energy efficiency in the short term in these industries. The reports from LBNL, for example, list 30–40 technology options for each industry, where about half of the technologies are already economic with a short return on investment. Many other studies of industrial energy efficiency point out that there is considerable scope for improvement even with existing technologies if one looks at energy efficiency as an isolated factor. However, there are many obstacles to change, as noted. Most of these technologies are consistent with the WEC goals of *Accessibility, Availability,* and *Acceptability* and often with very low technical commercial, environmental and regulatory risks.

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B. Buildings

Currently, buildings consume slightly more than 30% of the world's energy. The A and C scenarios in Part II indicate that the buildings sector worldwide may be using between 137 and 164 EJ per year in 2020, compared with 120 EJ in 2000. While current energy use in buildings is slightly higher that that of industry, it is interesting to note that the high end in 2020 is significantly below that of industry, indicative of significantly more conservation and the use of energy-efficient technologies. In 2050, the scenarios indicate 138 EJ for C and 229 EJ for A, a 115% and 190% increase over today. Again, this can be compared with the previous values given for industry of 143% and 250% for C and A scenarios, respectively. The energy savings due to new technologies can be estimated for the buildings sector by taking the difference between the A and C scenarios. Thus, global energy savings can be as much as 20 EJ/yr in 2020 and 90 EJ/yr in 2050, with Asia, Europe and North America, being the largest users today, having also the largest potential savings from introducing new technologies.

This part covers buildings themselves, the envelope and the appliances used within buildings (such as cooking appliances and fuel cells), as well as advanced management and communication systems. In addition, it deals with the interplay of the supply system. Energy consumption in the building sector in different regions is assessed, as are possibilities for efficiency improvements and savings in relation to the scenarios chosen for reference (A1, A3, and C2). Special attention is devoted to differing conditions in various regions of the world, including the special needs of Eastern European countries in their transition to free-market economies as well as developing countries in general. Many of the technologies (**Table III-3**) are common to the four sectors covered in this report (Industry, Transportation, Crosscutting, as well as Buildings). In turn, many crosscutting technologies (see Part III.D) are important to the buildings sector.

Residential and commercial buildings typically last for many years—30 to 50 years and some much longer, at least in the developed world. Hence, many of today's buildings will likely still be standing in 2020 and 2050. Parts of buildings may be changed through modifications and retrofitting—improved insulation, new windows and doors—perhaps as often as every 10 or 20 years. However, appliances within the buildings will be replaced at a much higher rate.

Today, energy consumption in the European Union for households and services makes up about 25% of the total (**Figure III-15**),[1] and is typical of much of the developed world. With regard to Eastern Europe and Russia and for the developing countries, there are large differences. For climatic reasons and because of differences in building standards, there are large variations between regions and countries.[2] Expectations to 2030 are also very different from region to region (**Figure III-16**).

Common to all regions of the globe is substantial potential for efficiency improvements through the use of new materials, intelligent systems, and enabling technologies. With regard to equipment and appliances, similar trends are also observed. Common to the

Table III-3. Building systems covered in this section.

Envelope	Insulation Windows Factory-built buildings with integrated envelope and equipment systems Building materials using recyclable materials Thermal storage materials
Equipment and appliances	Heat pumps Cooking appliances Fuel cells, solar photovoltaics, and microturbines Low-power lamps Refrigeration by alternative means High-efficiency centralized lighting Water heating
Intelligent systems	Automated diagnostics Advanced sensors Integrated control networks Stand-by
Enabling technologies	Advanced materials Measurements and control Modeling and simulation

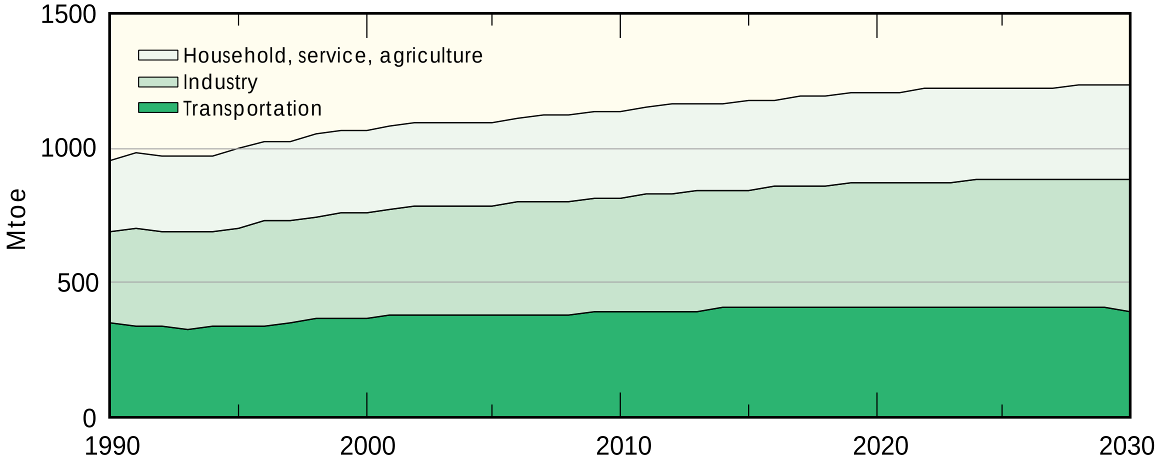


Figure III-15. Energy consumption scenarios in the European Union by sector (Source: *World Energy, Technology and Climate Policy Outlook*, WETO 2030, EUR 20366, Brussels 2003).

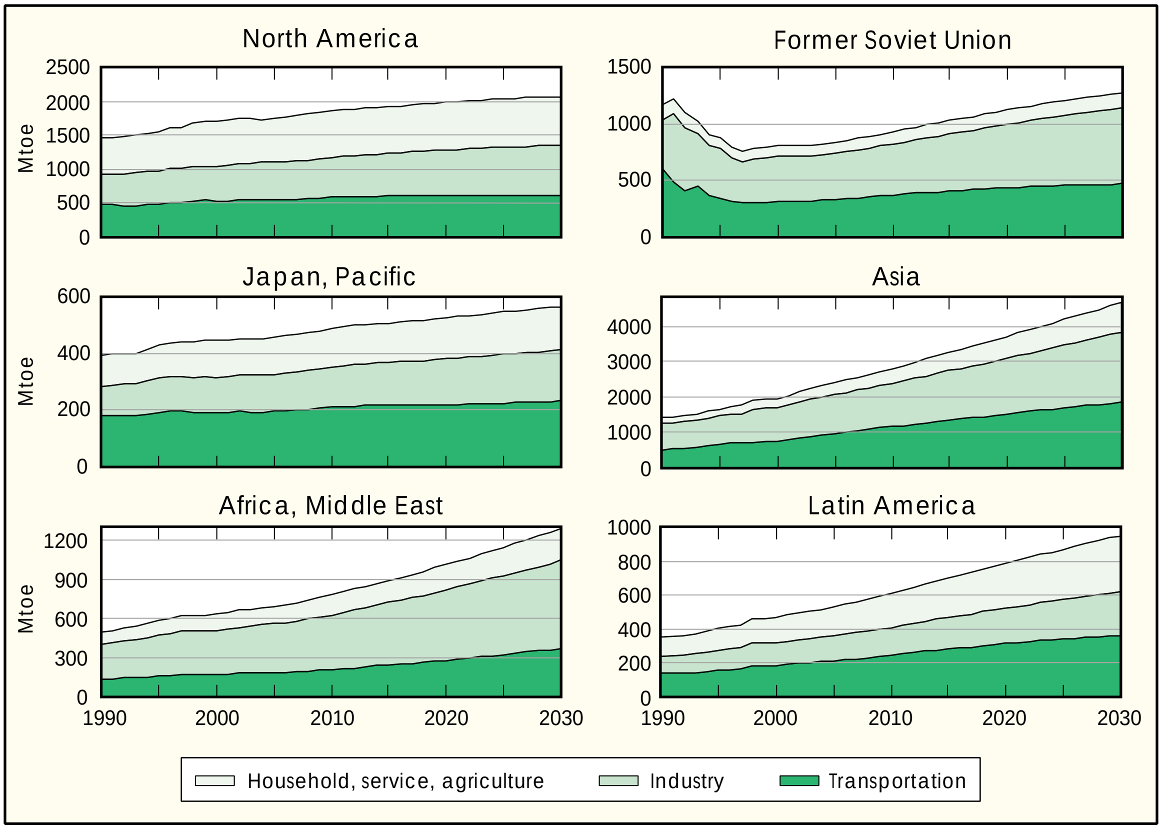


Figure III-16. Energy consumption scenarios outside the European Union (Source: *World Energy, Technology and Climate Policy Outlook*, WETO 2030, EUR 20366, Brussels 2003).

scenarios, the economic development expected for 2020 and 2050 point to a significantly improved standard of living throughout the world in general—although to varying degrees—and in the developing countries in particular. Growth in all regions will almost all take place in urban areas, mostly in large cities. This development will call for more energy services for buildings. Hence, an overall objective of the building sector is to assess the demand for improved energy services and the possibilities of efficiency improvements. Developing countries throughout the world will demand the same improvements in energy efficiency as the developed world in their service and industrial buildings. Obviously, for climatic reasons, the demand for efficient air-conditioning is higher in lower latitudes where many of the developing countries lie. For private homes, in particular in poor regions, the demand for inexpensive and efficient solutions for improved envelopes as well as for household appliances is large.

It is difficult to draw general conclusions about the energy demand of the developing countries and the potential for savings in their residential buildings because of the wide range of climatic, geographic, and socio-economic conditions. Nevertheless, the majority of inhabitants are poor and are likely to remain so, at least in relative terms, for some time in the future in spite of best efforts to alleviate their poverty. This means that low-cost or zero-cost options for saving energy and improving residential energy use and comfort levels are of critical relevance—equal to improving access to affordable, nonpolluting energy sources. This deals directly with the energy *Availability* and *Accessibility* goals found in the 2000 WEC Millennium statement.[3] While it is often imagined that energy conservation is not immediately important for developing countries—they should increase their energy consumption to improve their living standards—there is convincing evidence that the poor spend a significantly higher percentage of income on energy services than the more wealthy due to lower standards of housing, lack of access to modern energy sources, inefficient conversion devices, and other factors.

For private homes, in particular in poor regions, the demand is high for cheap and efficient solutions for improved building envelopes as well as for appliances. For most low-income households in developing countries, the choice of energy for cooking, lighting, and heating is often not a choice at all—whatever fuel is available and affordable is used. Cooling (air conditioning), while extremely energy-intensive, is seldom a major end-use in the residential sector in most developing countries at present, being confined to the wealthy minority that can afford it.

Compared with other sectors, the building industry in general is fragmented and performs little of its own R&D, and as such, depends heavily on government innovations and incentives. The industry is active in demonstrations of technology developed by governments (national laboratories and universities). Furthermore, only international (non-governmental) organizations and only a small portion of private industry study future prospects of this sector in the various regions in the world. (General background information on energy use in buildings may be found in References 4 through 9.)

1. Envelope

Since the first oil crisis in 1973, significant improvements in efficient energy use have taken place in many countries, in particular in OECD countries with high demand for heating during cold winters. New houses in Nordic countries require less than half the annual amount of energy for heating than old houses.[10] The development of new, better insulation materials and the use of advanced double or triple glazing in windows achieved this reduction. Also, many old houses have already utilized significant improvements through retrofitting, which has become more cost-effective due to higher energy prices (**Figure III-17**). An important factor in this development has been the introduction of new building standards with strong compulsory rules on insulation thickness, tightness, ventilation, etc. Another factor has been the introduction of energy taxes, making these improvements cost-effective for private households.

According to the European Insulation Manufacturers Association,[11] energy consumption for heating varies greatly between countries and is much higher in some low-latitude countries due to very low insulation standards (**Figures III-18** and **Figure III-19**). Further, there are great differences in costs between commercial buildings and residential buildings. Nevertheless, much can still be done.

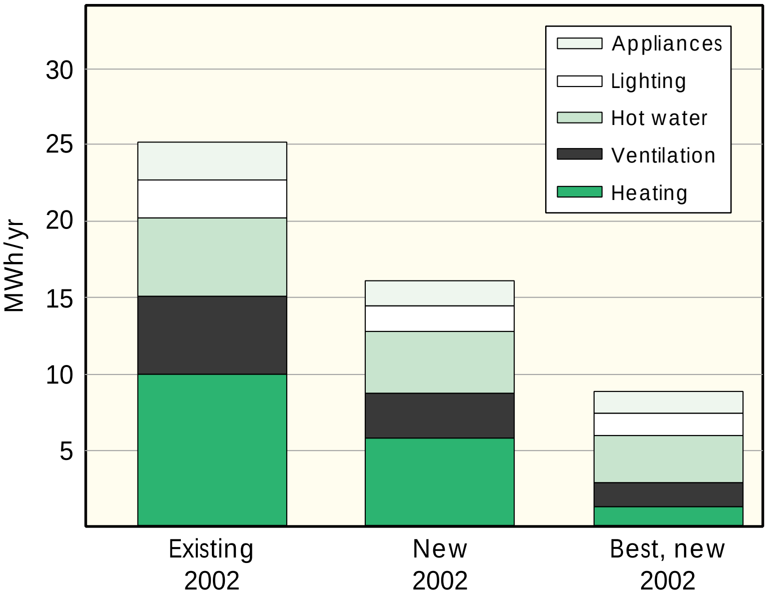


Figure III-17. Energy Consumption in Single Family Homes in Sweden (Source: Swedish Academy Foresight for Sweden study, "Energy Foresight—Sweden in Europe," Royal Swedish Academy of Engineering Sciences, IVA, Stockholm, 2003).

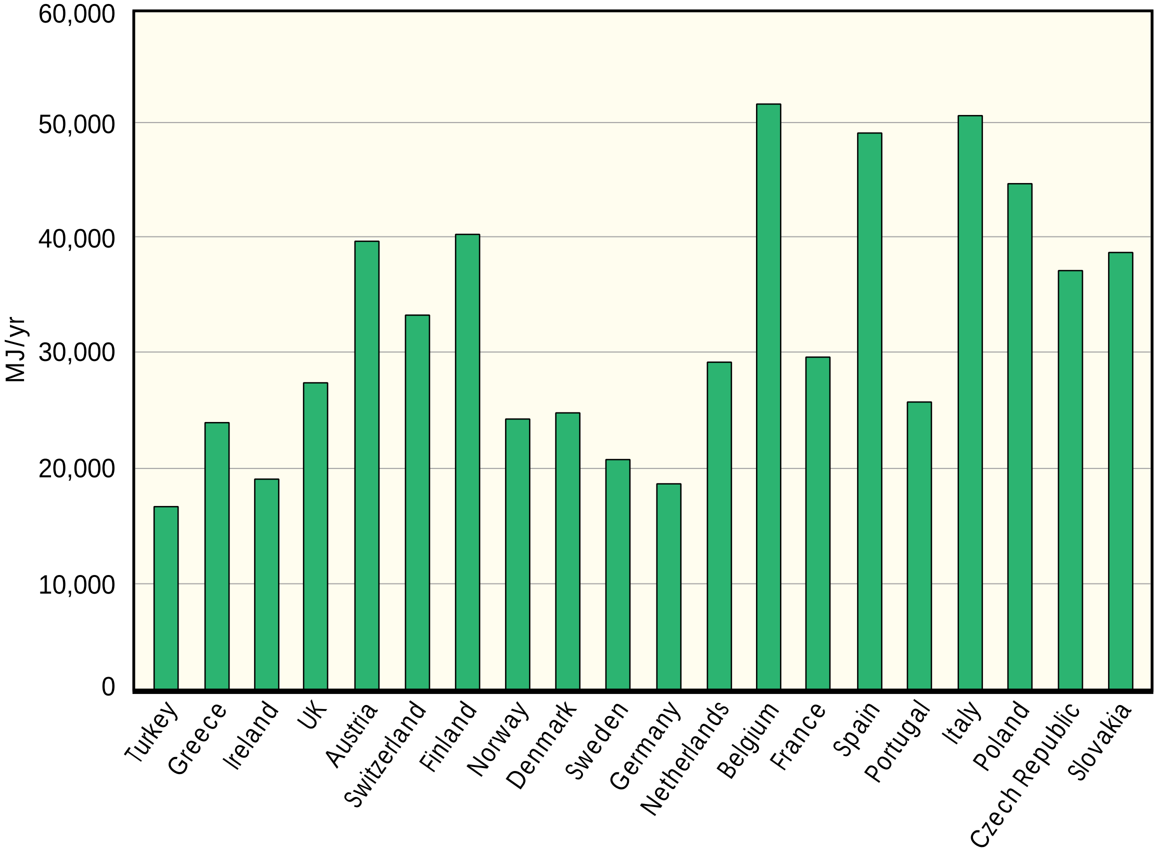


Figure III-18. Annual Dwelling Energy Loss in Europe (Source: *The Contribution of Mineral Wool and other Thermal Insulation Materials to Energy Saving and Climate Protection in Europe*, ECOFYS for EURima [European Insulation Manufacturers Association], December 2002).

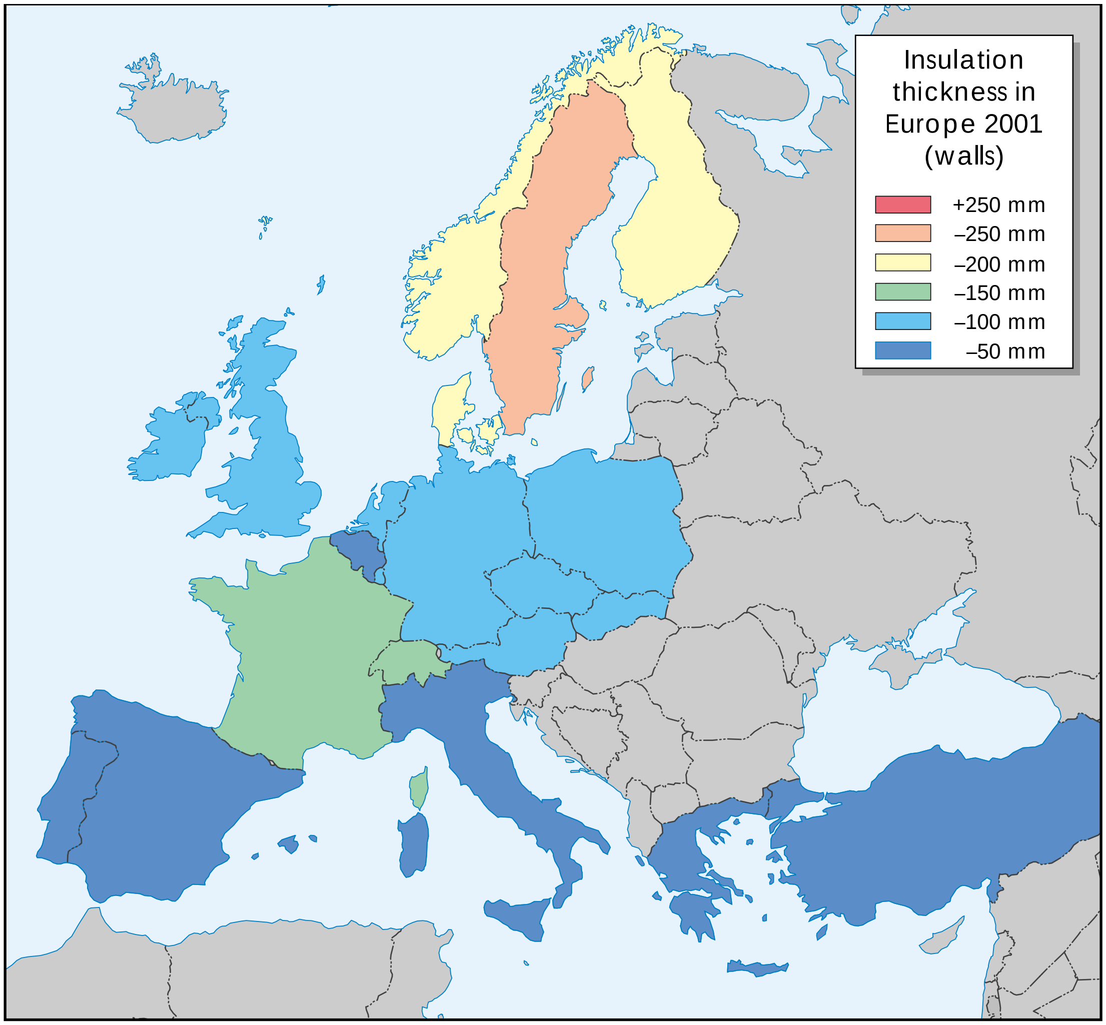


Figure III-19. Building Wall Insulation Thickness Requirements (new construction in Europe) [Source: *The Contribution of Mineral Wool and other Thermal Insulation Materials to Energy Saving and Climate Protection in Europe*, ECOFYS for EURima (European Insulation Manufacturers Association), December 2002].

A question concerning the development of the building envelope is whether the concept of “zero-energy” houses is feasible. The answer from a technical point of view is yes, provided we define zero energy as zero energy for heating and cooling. With heavy insulation, recirculation of indoor air, use of waste heat from appliances, passive solar heating, etc. this is certainly feasible in the higher, more populated latitudes. What cannot be concluded for the long-term future is (1) what the costs of converting to such a concept are, (2) whether the indoor climate would be acceptable (air temperature), and (3) whether that type of sealed house meets future costumer preferences and environmental regulations (air quality). Market forces alone are unlikely to bring about such efficiency improvement, and government research and policies are needed.

The technologies to a large extent are already available to build new “very-low energy” houses. Apart from building highly insulated houses, it is possible to design the houses with passive solar heating (and cooling) and include energy storage or sinks in the walls, roof, and floor. Combining this with smart sensors and intelligent systems, it is possible to store or remove heat when available and use it when and if needed. Windows may be designed with coatings, allowing the selective transmission of sunlight. More research is needed for such systems and the costs reduced if the demand for such houses is to develop. It should be possible to move the technologies down the learning curve to make them competitive in the marketplace.

As mentioned earlier, the building industry is rather fragmented and performs little of its own R&D, and depends on the government and universities for innovations and incentives. For that reason, it is difficult to predict the likelihood of major breakthroughs before 2010, 2020, 2030, etc. related to the construction of the envelope. There are possibilities for major efficiency improvements in terms of factory-built dwellings and spin-offs from other industrial sectors, resulting in cheaper and less bulky insulation materials. (General background information on energy use in buildings may be found in References 12 and 13.)

With regard to existing buildings, a great deal can be achieved to save energy through the retrofitting of both private homes and commercial buildings. As outlined in both References 14 and 15, it is much more economically feasible to add energy-related retrofitting when buildings are being retrofitted for other reasons. The alternative is to make it compulsory through stricter building codes for both new and existing buildings and dwellings.[16] Retrofitting old residential buildings with energy conservation measures provides reduced energy consumption and demand. It may also lead to lower peak demand. In the case of Kuwait, with a hot and arid climate, the payback time for retrofitting is very long[17] due to highly subsidized electricity prices. It is of paramount importance that energy prices reflect real costs. This requires introducing environmental costs to make retrofitting attractive from an investor’s point of view.

Standards for existing building stock vary considerably between regions and countries. These differences to some extent are for climatic reasons and the need for heating and/or cooling. However, socio-economic factors, consumer prices, and incentives also play a major role. In Eastern Europe and Russia, the existing building stock is in very poor condition, especially with regard to energy consumption. One of the reasons is that the energy supply to a large extent has been based on district heating and natural gas with extremely low consumer prices, providing only little or no incentive for consumers to reduce consumption. Hence, there is room for much improvement, especially with regard to insulation and thermostats as well as changes in the pricing structure. Obviously, for climatic reasons, the demand for efficient air conditioning is higher in lower latitudes.

Low winter temperatures, around or below freezing, are common in the many high altitude and inland areas of the developing world, such as Southern Africa (three quarters of the area of the region), South America, and China. In these areas, typified by cold winters and hot summers, great advantages can be gained from design considerations such as orientation of the house (in the southern hemisphere with windows facing north), window size, design, and position, and ceiling installation. All of these elements considered at the construction stage can substantially reduce energy demand at little or no additional cost. For example, the installation of a simple ceiling in a house with a corrugated iron roof can reduce heating demand by as much as 74%, and even more if insulating material is included (**Figure III-20**).[18]

These and other low-cost interventions, primarily targeted at low-income households, may be encouraged best through industry and government information and demonstration programs, persuading such households of the economic and comfort gains to be obtained. Formal building standards, though often present in developing countries and incorporating such issues, or not always observed or enforced. An analysis points to the need for new and innovative financing mechanisms to assist poor communities (in South Africa for example) to capture the benefits of energy efficiency.[19] **Tables III-4** and **III-5** characterize the state of insulation and of window technologies, respectively. Note that discussion of the risk factors involved is left to the text in this part.

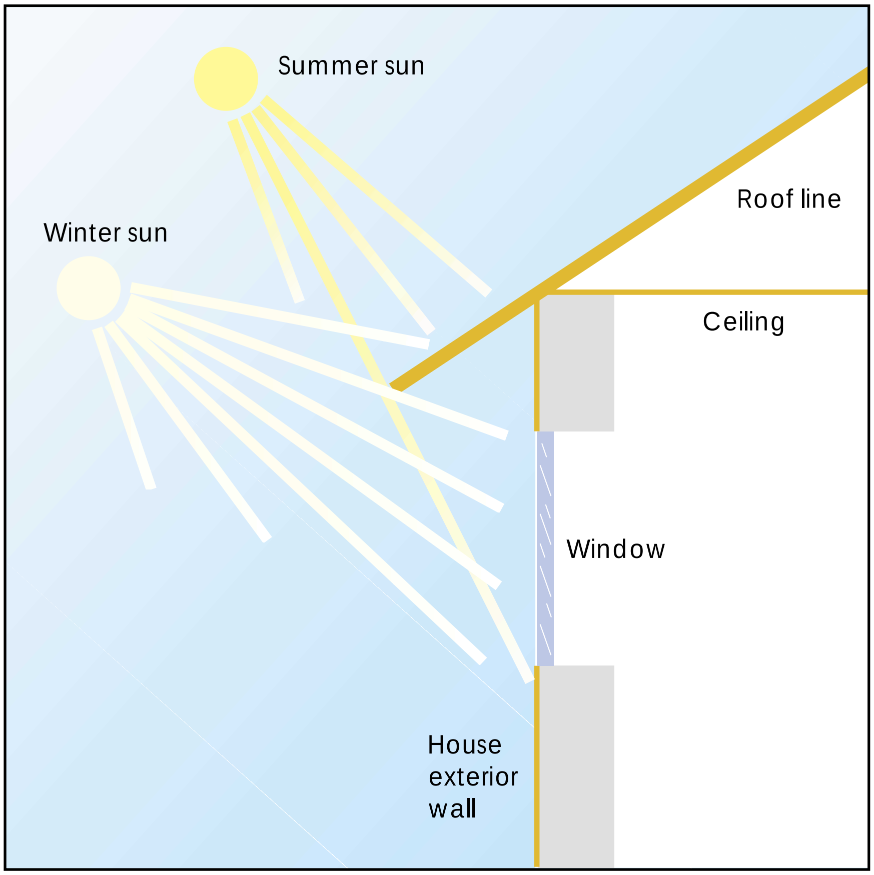


Figure III-20. Illustration of the potential heating and cooling effects gained by simple building design. (Note hidden costs may act as a barrier, e.g., the need to seal the house against animals that "colonize" the attic area, using insulation material for nests).

Table III-4. Advanced insulation technologies.

	Advanced Insulation	Remarks
System Concept	Improve insulation in roof, walls, and floor with low U values	
Description	Thermal insulation, e.g., mineral wool	
Technology Status	In progress, new materials under development with lower thermal conductivity	
RD&D: Goals and Challenges	Zero-energy house—new houses Retrofit existing houses	
Benefits and Costs	• Cost:	Moderate
	• Efficiency:	Yes
	• Reliability:	High
	• Energy quality:	Acceptable
	• Environmental Impact:	Low
	• Economic impact:	Acceptable
	• Customer Preference:	Depending on the cost and payback time
Risk Factors	• Technical:	Low (2-3)
	• Commercial:	Low (2-3)
	• Environmental:	Low (2-3)
	• Regulatory:	Low (2-3)

Table III-5. Advanced window technologies.

	Advanced windows	Remarks
System Concept	New types of windows based on advanced materials	
Description	• New windows using advanced materials with low thermal conductivity • New windows with built-in solar cells	
Technology Status	In progress – continuous improvements	
RD&D: Goals and Challenges	Close to zero net loss through windows	
Benefits and Costs	• Cost:	Perhaps
	• Efficiency:	Yes
	• Reliability:	Acceptable
	• Energy quality:	High
	• Environmental impact:	Low
	• Economic impact:	Moderate
	• Customer Preference:	Depends on cost
Risk Factors	• Technical:	Low (2-3)
	• Commercial:	Low (2-3)
	• Environmental:	Low (2-3)
	• Regulatory:	Low (2-3)

2. Equipment and Appliances

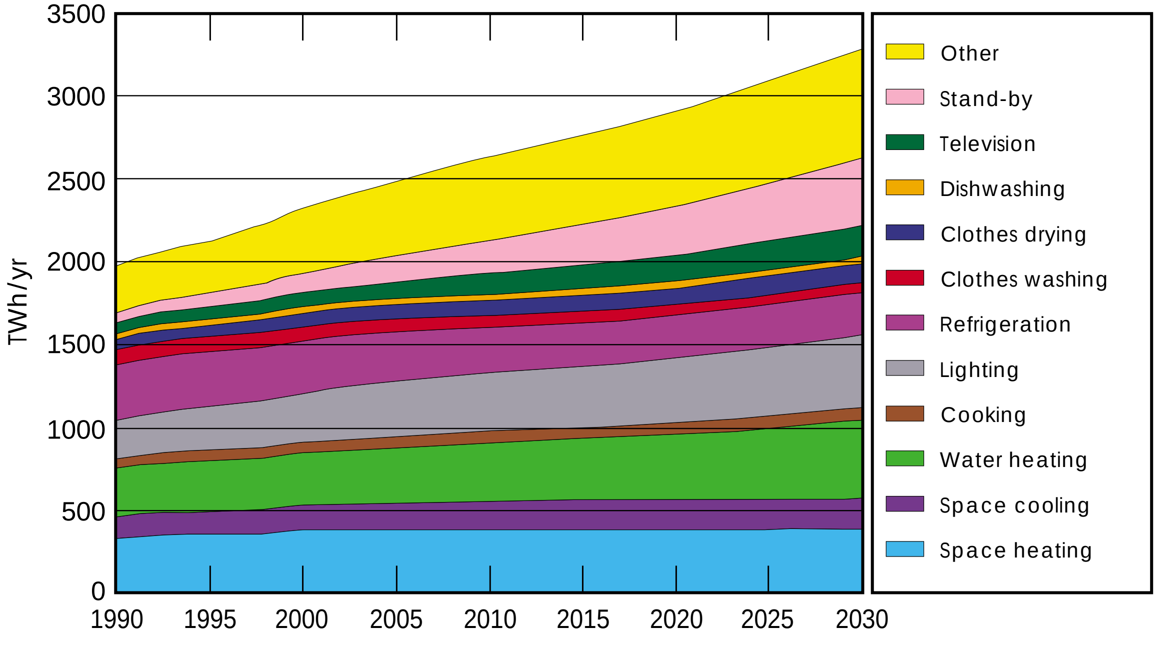
This section deals with energy supply and conversion technologies used locally in the building itself for space heating, water heating, and electricity production (e.g., small fuel cells). The section also deals with end-use appliances for cooking, lighting, and refrigeration. Electrical appliances are the fastest growing energy end-users, after automobiles (**Figure III-21**).[20]

Fuel Cells

Fuel cells may in 10 to 15 years replace existing heating systems fueled by oil, natural gas, or electricity in private homes and commercial buildings. Fuel cells produce both heat and electricity. Proton Exchange Membrane (PEM) fuel cells and Solid-Oxide Fuel Cells (SOFC) fuel cells are promising and of interest for buildings (**Figure III-22**).[21,22]

Foreseeable applications for fuel cells (with typical fuel-cell types and power ratings in parentheses) are—

- Portable electronics (DMFC) (1–200 W)
- Domestic heat and power (PEM, SOFC) (5–200 kW)
- Electric road vehicles, including trucks (PEM) (50–200 kW)
- Ships (>MW)
- Power stations (SOFC) (>>MW).



(Source: International Energy Agency)

Figure III-21. Real and Projected Appliance Electricity Demand (Source: Policy Strategies for Energy Efficient Homes, IEA, April 2003).

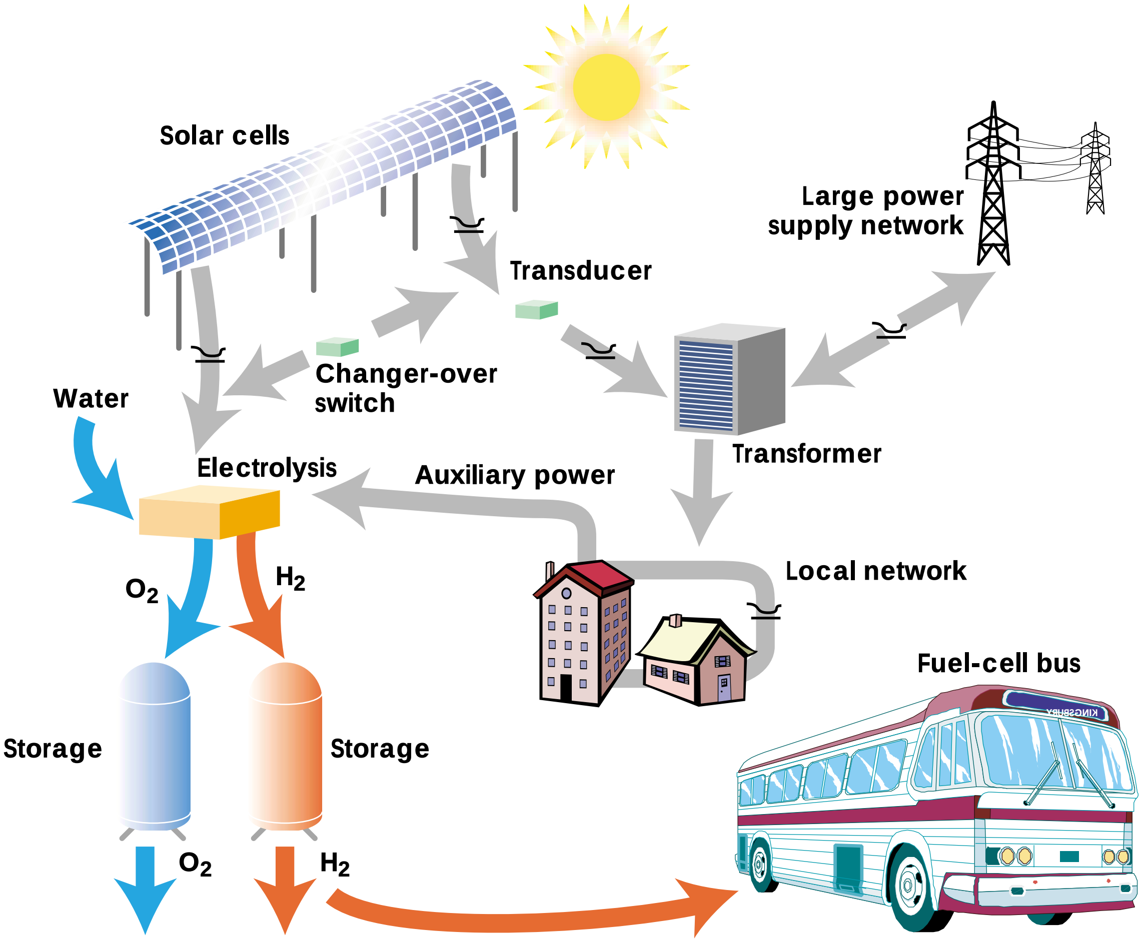


Figure III-22. An Integrated Energy End-use System (Source: Swedish Academy foresight for Sweden study, "Energy Foresight—Sweden in Europe," Royal Swedish Academy of Engineering Sciences, IVA, Stockholm, 2003).

The last four of these applications have massive beneficial economic and environmental impacts, including the creation of new high-tech industries (see Part III.D.1).

One possibility in single-family houses is Micro-Combined Heat and Power (micro-CHP) generators based on fuel cells or small power units. A micro-CHP is designed to operate in parallel with the existing power grid. Fuel cells are based on stacks and are therefore flexible in size and may be used in both smaller and larger units. Fuel cells have a high potential efficiency (e.g., 45% electric and 70% total electricity plus heat). The cells may be fueled either directly with hydrogen or natural gas in combination with a reformer.

Heat Pumps

Heat pumps are already used in some parts of the world, in particular in countries with an ample supply of cheap electricity from domestic resources (e.g., hydropower). Further R&D may make heat pumps more generally competitive. They can be used for simple heating, including water heating in individual houses, by using the waste heat in highly insulated houses. Micro-turbines might also become an attractive alternative for heating.

Solar Photovoltaics

Solar Photovoltaic (PV) cells convert the sun's energy directly into electricity. The power from solar cells is presently far more expensive (up to 10 times) than conventional sources of electricity. However, the learning curve for the cost of PV modules show that the cost is rapidly coming down, indicating a 20% reduction in cost for each doubling of cumulative production, although that percentage will decrease as the commercial market is approached.[23] The U.S. *Photovoltaic Industry Roadmap* predicts a worldwide shipment approaching 18 GW per year by 2020.[24] Decentralized generation is feasible with PV systems because they require few or no system operators, do not pollute, and are noiseless. Because the cost per kilowatt-hour of PV electricity may be relatively insensitive to the scale of the installation (see Reference 21), PV systems are well suited to be integrated in individual buildings. Cells can be fabricated as an integral part of the roof, the walls, or even the windows. However, it is worth remembering that the average power from solar PV units is usually 10 to 20% of power capacity due to local conditions and diurnal cycles.

Refrigeration

As can be seen from Figure III-21, energy demand for refrigeration is not expected to grow much in the coming two decades. This is probably due to the fact that the market for this is almost saturated, at least in the OECD countries. The competition in this area is already driven to some extent by the energy consumption by each unit. Customers are very focused on energy use in this area. Obviously, there is room for efficiency improvements, but they are well underway. There might be possibilities for technological breakthroughs with regard to alternative refrigeration means and methods that would result in significant energy efficiency improvements. These include Stirling cycles, Brayton cycles, and acoustic, magnetic, and thermal-electric technologies.

Lighting

As also seen from Figure III-21, energy demand for lighting is expected to grow over the next two decades. The most obvious possibilities for energy savings are lifestyle changes, cost incentives, and technological improvements or breakthroughs. Simple lifestyle changes such as convincing people to switch off lights will be difficult in the richer societies of the future. This will probably only have an impact if it is facilitated by smart systems that switch off lighting when not in use. The development of these technologies (see Part III.D.7) can be stimulated by cost incentives, such as variable electricity prices. Even in a future situation where the individual house is producing part or all of its electricity internally, the cost incentive might be valid as an alternative to using the electricity internally and instead selling the electricity to the grid. The possibilities for savings through new technological developments are large. The low-energy bulbs of today could be widely deployed, giving rise to large savings. Low-power lamps can be further developed together with hybrid lighting systems that utilize high-efficiency centralized light sources and controlled application of day lighting.

Electronic Appliances

Residential buildings are rapidly being equipped with numerous new electronic appliances such as computers, automatic devices, and communication equipment, among others. Many of these devices are being used or are in stand-by position throughout the entire day and night. In 2003, it has been estimated by the Danish Energy Agency that about 10% of electricity use in private homes is "wasted" on stand-by.[25]

In many new commercial buildings, numerous electronic devices run in open-space offices longer than the working day. In some cases, these areas are lit nearly 24 hours a day. Similarly, the Danish Energy Agency has estimated that about 40% of electricity in commercial buildings in Denmark is used outside normal working hours, the major part in the stand-by mode of electronic equipment (see Reference 25). This situation is exacerbated by flexible working hours with the result that at least a few persons are always present with all of the equipment running. Hence, there is room for substantial optimization with regard to energy use.

In this area, prospects for technological breakthroughs are considerable, although difficult to predict. One thing is certain—information technology and sophisticated electronic devices will be improved rapidly, opening new possibilities for dealing with this problem, and if handled in a clever manner, it should be possible to minimize energy consumption. Individual technologies are rapidly becoming more energy-efficient, but the ever-increasing development of new pieces of equipment increases electricity consumption at the same time.

In the long run, developing counties throughout the world have in principle the same needs for appliances as the rest of the world. However, the starting point is quite different.

Cooking

Biomass (for example, firewood, charcoal, and plant or animal residues) is still the dominant fuel used for cooking in most developing countries. There is some scope for solar cooking mainly in the special case of institutions where food is prepared in the middle of the day. For the majority of developing-country households, the alternatives to biomass are kerosene, liquefied petroleum gas (LPG), and electricity. Electricity is seldom preferred as a cooking fuel for a number of reasons not the least of which is the cost of cooking appliances and the cost of the electricity to run them. Moreover, electrification in many developing countries is still only about 10–20% and unlikely to rise above 30% in the foreseeable future. A clean alternative is required to move the millions of households away from biomass.

The most promising cooking fuel is generally recognized to be LPG, and major efforts are already under way to meet the challenge of increasing the access to this clean and convenient fuel (e.g., the LP Gas Rural Energy Challenge[26]). Although it should be pointed out that LPG is a fossil fuel and thus contributes to greenhouse-gas emissions, it has been argued by the World Liquid Petroleum Gas Association (see Reference 26) and K. Smith[27] that even if 2 billion people shifted to LPG, it would mean an increase of only

2% in the greenhouse-gas emissions from fossil fuels. A major challenge in increasing access to LPG is improving the distribution network for the fuel, encouraging retailers to establish distribution depots and sales outlets in remote and sparsely populated areas. Clearly, this will require special incentives, cross-subsidies, regulation, etc.

In South Asia and Africa, where energy from traditional biomass accounts for up to 90% of energy consumed by rural households (and cooking accounts for about 90% of energy consumption), moving away from biomass towards LPG is not easy in some countries exporting LPG and other petroleum products. The energy transition will take long time for many poor households. However, the use of sustainable biomass should be also an alternative for cooking, for example:

- High-efficiency cookers fueled by mini-briquettes made from locally available biomass crops and waste products.
- More efficient cookstoves utilizing simple, promising new technology.

These sustainable, biomass-based technologies—if improved in the future—could be appropriate for poor people in rural areas, and will help reduce CO_2 emissions and have substantial effects on forest conservation.

Cooking with solar heat is a promising and valuable alternative in rural areas of developing countries because it can be mixed with other cooking technologies, such as improved cookstoves using other cooking fuels, and food is usually prepared in the middle of the day, and it is usual that these people eat the same food once a day. It is expected that the market share of solar cookers and improved cookstoves may increase significantly in rural Asia and Africa by both 2020 and 2050.

Solar Water Heating

There is a large potential for solar water heating, particularly among households who already use significant amounts of energy (electricity or gas) for heating water and particularly in the lower latitudes. In many parts of the developing world, for example southern, eastern and western Africa, this is confined to the relatively affluent few. In Mediterranean regions, however, there is a very highdemand today. In Tunisia for example, the use of hot water (normally using natural gas) is set to grow in both the domestic and tertiary sectors towards 2010, the potential market for solar water heaters is estimated at 1.5 million m^2 collectors, with 32,000 m^2 having been installed by 2003. For 2010, the solar program is aiming at a total of 1 million m^2 of solar collectors, thus saving on average 100,000 toe per annum and avoiding the release of 300,000 tonnes of carbon dioxide into the atmosphere.[28] Similar conditions apply in other North African countries such as Morocco.

The major constraint in achieving these goals is financing. A UNEP-led collaborative activity, MedREP, backed by the Italian government, is currently investigating novel financial schemes for increasing the share of renewables in these countries.[29] **Table III-6** characterizes the state of fuel-cell technologies for buildings.

Table III-6. Fuel-cell technologies for buildings.

	Fuel cells in individual homes	Remarks
System Concept	Modular fuel-cell systems	
Description	• Proton Exchange Membrane (PEM) • Solid Oxide Fuel Cells (SOFC)	
Technology Status	• At research and demonstration stage • Good progress	Commercial use expected from 2010
RD&D: Goals and Challenges	• Commercial competitive modular units to replace oil or gas units in individual homes	
Benefits and Costs	• Cost:	Expected
	• Efficiency:	Yes
	• Reliability:	No
	• Energy quality:	Good
	• Environmental impact:	Improvements
	• Economic impact:	Moderate
	• Customer Preference:	Cost-dependent
Risk Factors	• Technical:	Moderate (4-5)
	• Commercial:	Moderate (5-6)
	• Environmental:	Low (2-3)
	• Regulatory:	None

3. Intelligent Systems

In 2020 and even more in 2050, new buildings are likely to be equipped with numerous sensors, monitoring systems, and intelligent energy-management systems (see Part III.D.7 and D.8). Such equipment will make it possible for the building envelope, as well as all the appliances in the house, to adapt automatically to changing needs and conditions in response to external or internal environmental conditions. The buildings’ sensors and monitoring systems will support startup, operation, and maintenance and advise or decide on necessary repair work. At the same time, the buildings will be part of a large, integrated supply net with a combination of large and small producers; the building is both buying and selling energy to this system (**Figure III-23**).

Such advanced buildings are likely to be equipped with two-way communication between end-use and supply, particularly in the case of a renewable energy supply, which should give rise to substantial overall efficiency improvements. An example is a building envelope with an adjustable storage capacity and windows with adjustable transparency combined with appliances such as washing machines, dishwashers, etc. that might be switched on when there is a surplus of internally generated electricity. Alternatively, the electricity can be sold to the local net at a favorable price, by means of a price-responsive, energy-use control. These systems are expected in the years ahead to enter first in new private houses, but will also gradually enter existing buildings during retrofitting. With office buildings, some of the monitoring equipment and energy management systems are already

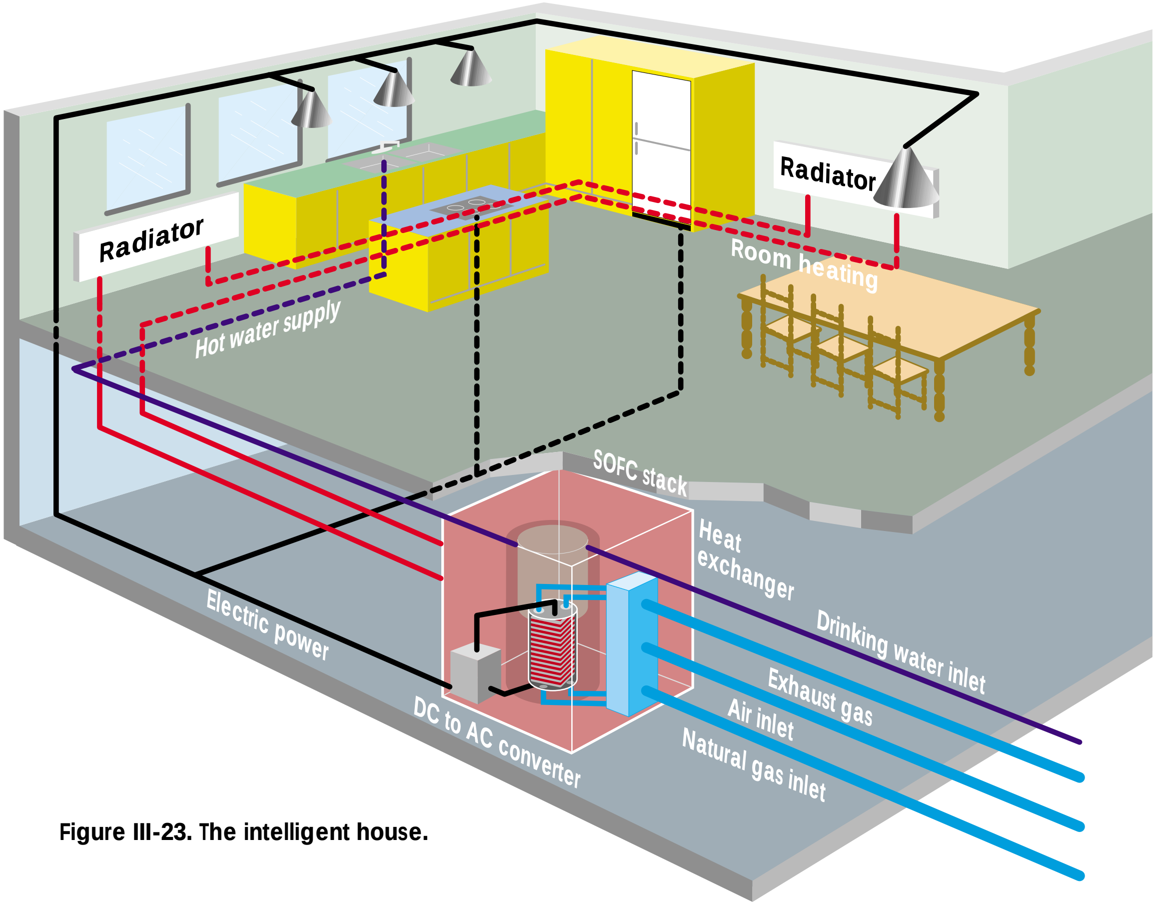


Figure III-23. The intelligent house.

used to a large extent, and it is likely that office buildings will continue to be ahead of private homes in this regard.

Over the timeframe to 2050 analyzed in this report, hydrogen is likely to enter the transportation sector to some degree as a fuel in private cars equipped with fuel cells (see Part III.C.4). Private cars are typically only used for driving part-time or even a few hours a day. It will be natural to try to use the fuel cells in the car parked outside the family house as an energy source to provide heat and/or electricity to the house. Such a system obviously calls for even more advanced energy-management systems combined with energy storage and backup supplies. More RD&D is needed before such solutions can be implemented at normal market conditions. However, attention should be paid to this attractive solution.

Stand-by

There is considerable room for substantial efficiency gains with regard to all types of equipment running many more hours than necessary for designated tasks. The energy use of individual pieces of equipment is continuously improved by manufacturers. These separate improvements, however, leave out the combination of all equipment running throughout the workday, now longer due to flexible working hours in commerce and the desire to have communication and computer equipment available throughout the day in private homes. Intelligent systems that fulfill these demands and avoid wasting energy in stand-by mode at the same will be very useful. Smart buildings equipped with advanced sensors and energy control and monitoring systems are the future. Lifestyle changes have always entailed a lengthy process; however, in this case, the modern culture of young people having grown up with Internet communication and mobile phones available 24 hours a day makes electronic decisions on energy supply and demand much easier. Decisions on energy supply coupled with on-line pricing and demand might very well fit in with other actions taken in individual homes such as electronic banking and purchasing of food in the local supermarket.

Considerable energy could be saved today if individual families gave a higher priority to energy efficiency and usage. There must also be a willingness to spend the necessary time on energy management decisions, e.g. switching off lights and other electronic equipment in the house and turning down the heat when appropriate. Most consumers are more focused on comfort and convenience, and for that reason, only limited energy savings are typically achieved. In the future, it is likely that convenience will be given more priority than today. Hence, the way forward is to introduce intelligent systems that manage household energy without reducing the comfort and the convenience of the family.

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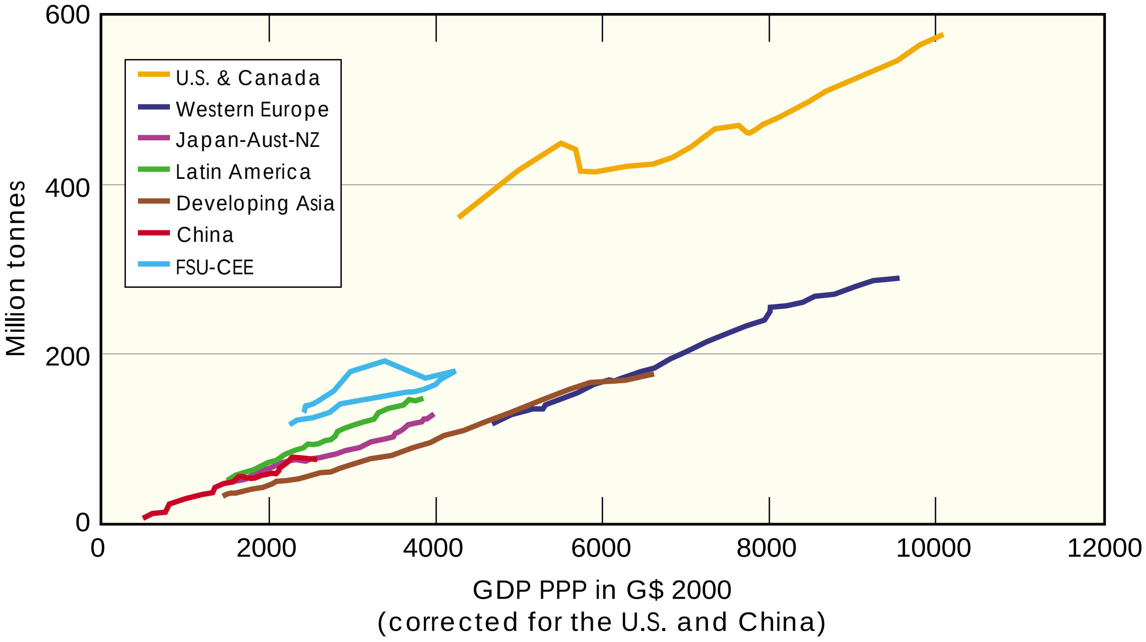
C. Transportation

Transportation is a critical end-use sector of energy. It currently uses about 20% of global primary energy (80 EJ/year), and in the scenarios presented (see Part II), is expected to grow between 150 and 280% by 2050 (120 to 225 EJ/year). Energy savings from new technologies, estimated as for the previous two sectors (industry and buildings), can be as much as 40 EJ/year in 2020 and 105 EJ/year in 2050. The largest savings by region (20% of total) is estimated to take place in the former Soviet Union, with one-half of that amount achievable by 2030 (freeing a suppressed but high-tech economy). Transportation provides people with mobility, it moves goods and services, and because much of the primary energy comes from petroleum, which in turn is concentrated in localized areas of the world, it is the sector most at risk of being disrupted, either by economic conditions or political situations. There is no evidence of saturation in the markets for transportation services in developed countries (**Figure III-24**). This, coupled with rapid growth in developing countries, places emphasis on the future of the transportation end-use sector. Such emphasis assumes that the GWP will support imagined growth in the transportation sector, and that high-population countries like India and China will be dominant in the development and use of new transportation technologies.

A closer examination of the three scenarios considered in this study yields an insight into the end-use demand for transportation services worldwide and its prospects **(Table III-7).** The data, in terms of distances traveled, are broken down by both passengers and freight.



(Source: IEA)

Figure III-24. Regional mobility trends (Source: *Drivers of the Energy Scene*, World Energy Council, December 2003).

Table III-7. Distance traveled for passengers (10^{12} person-kilometers/year) and freight (10^{12} metric tonne-kilometers/year) in three scenarios described in Part II. Numbers in parentheses are the percentage increases after 2000. Note that all numbers are rounded and may not sum exactly.

	Scenario	2000	2020	2050
Passenger Air/Road	A1	27	45(63)	83(202)
	A3	27	45(64)	85(212)
	C2	22	33(53)	55(151)
Passenger Rail/Water	A1	4	8(120)	24(535)
	A3	4	9(125)	25(549)
	C2	3	6(95)	14(358)
Passenger Total	A1	31	53(70)	107(242)
	A3	31	53(72)	110(254)
	C2	25	39(58)	69(176)
Freight Air/Road	A1	7	11(56)	18(154)
	A3	7	11(55)	19(157)
	C2	6	10(60)	16(160)
Freight Rail/Water	A1	15	20(30)	26(70)
	A3	15	20(29)	26(70)
	C2	12	16(25)	20(59)
Freight Total	A1	23	31(38)	44(97)
	A3	23	31(38)	45(98)
	C2	18	25(36)	36(93)

The scenarios project an increase in air and road traffic of greater than 50% in the next 20 years and close to 200% in the next 50 years. However, although much smaller now, rail and water traffic may grow by twice as much in the next 20 to 50 years, possibly more than 500% by 2050. This reflects a much larger population and a drive toward mass transit. Nevertheless, a doubling of the air and road passenger traffic over the next 20–30 years, with two-thirds of all traffic using these means, places a great deal of pressure on automobile and air transport technologies. What are these technologies and how will they meet the challenge?

Not to be overlooked is freight traffic that already accounts for 30–40% of energy use in the transportation end-use sector and is projected to grow by a factor of three over the next 50 years.[1,2] What technologies will facilitate this demand? Nevertheless, freight is expected to be a decreasing percentage of the total energy use and perhaps more like 30% by 2050. This is because of the growing influence of the automobile in high-population societies, such as China and India, and increasing efficiency in hauling freight.

Transportation is a very large and robust industry, but one whose horizon is in general shorter than the energy industry as a whole. Stock turnover of new automobiles is on the order of 10 years, whereas much fixed-energy industry stock turnover is 30 years or more. Thus, new end-use technologies in transportation are limited to some degree by a slower turnover in the types of fuels that can be utilized. While in this section we focus on specific end-use technologies, it is important to realize that the infrastructure attendant to the health of any technology is equally important. For example, an internal combustion engine today requires a gasoline production, transport, and distribution network for its efficient utilization. Other sectors also require similar infrastructures. In looking to the future, it seems logical that the marketplace might favor those end-use technologies that utilize existing infrastructures and also favor those that utilize infrastructures supplying other end-use technologies and market sectors. Thus, the use of existing electricity and natural-gas distribution systems to produce hydrogen at or near its end-use, say for small fleets of vehicles, seems to both favor the introduction of the technology and the simultaneous continued use of that infrastructure. Other examples are possible.

This part seeks to link transportation technology trends to both energy needs in general and to other end-use needs in particular (e.g., dual-use fuel cells). Further benefits can be obtained by examining specific actions that must take place for a technology to move into the marketplace. Key uncertainties center around the role played by two important technologies, fuel cells and hydrogen:

- Can fuel cells compete with the internal combustion engine?
- Will hydrogen be the majority transportation fuel, and if so, when?

There is a close link between fuel cell and hydrogen technologies because hydrogen is the primary fuel that fuel cells operate on.

The transportation industry is understandably very interested in delineating the roles of industry and government, as well as demarcating the line between near-term and long-term RD&D. An important factor in transportation is the diffusion of new technologies into the transportation fleet, which often takes place more rapidly than in other sectors. The World Business Council for Sustainable Development and the U.S. National Academy of Sciences/National Research Council have recently studied the transportation sector, providing useful information on the technologies examined here and on their impact.[2,3] The World Business Council's paper posits that to change the current path of greenhouse-gas emissions, the world must move to "carbon neutral" fuels (e.g., hydrogen and biofuels). The National Research Council paper shows persuasive evidence for the need to do this, using illustrations of various technologies, fuels, and combinations.

For the present study, the technologies most important to the transportation sector are separated into five categories:

1. Advanced Internal Combustion Engine Systems
2. Alternative Fuel Engine Systems
3. Hybrid-Electric Power Systems
4. Fuel Cell Power Systems
5. Other Power Systems (turbine, electric).

1. Advanced Internal Combustion Engine Systems

System Concepts

Advanced concepts applicable to vehicles include weight reduction, decreased drag, and efficiency improvements in drive trains and engines. Internal Combustion Engines (ICEs) account for essentially all vehicles today. Improvements in ICEs fall into two categories: spark-ignited engines and diesel. In addition, improvements are expected in exhaust after-treatment and in transmissions and drive lines. In addition new and improved fuels are expected, resulting in higher efficiency vehicles and reduced emissions into the atmosphere. Thirty to forty percent of the transportation energy used globally is to haul freight, most by diesel engines. New-generation, ultra-high-efficiency diesel engines with advanced emission-control technology and improved aerodynamics are reducing both fuel use and emissions. The efficiency of operation is a premium here because many of these vehicles operate in long-haul mode and more aerodynamic shapes designed using software and low-friction tires are among the non-engine technologies used. (For a more detailed description of these technologies, see the excellent roadmap available in Reference 4.)

Technology Description

For spark-ignited engines, reduction of cylinder displacement leads to increased efficiency. So does boosting (supercharging and turbocharging), direct injection with stratified combustion with advanced after-treatment, direct injection with homogenous combustion in concert with conventional after-treatment, variable valve trains allowing optimized torque, variable compression ratios (optimizing efficiency), and controlled auto-ignition. For light-duty diesel engines, downsizing with associated supercharging and intercooling, advanced fuel-injection systems with variable-size injection nozzle holes and injection patterns, and high-speed diesel engines also leads to more efficient engines. For the heavy-duty diesel engines involved in freight hauling, technologies include four-stroke, direct-injection diesel engines, and lightweight materials.

After-treatment technology is important for controlling emissions, be they local or global pollutants. The applicable technologies include three-way catalysts, advanced NO_x absorber catalysts, catalysts with reduced amounts of precious metals (which are therefore less expensive), advanced high-pressure injection, selective catalytic reduction, oxidation catalysts, diesel particle filters, advanced sensors, NO_x conversion technologies, and coatings for advanced catalysts.

New gasoline and diesel fuels are also under development. Techniques for removing sulfur, for creating diesel fuels formulated to lower NO_x and particulates, improved volatility and octane numbers, new bases and fuels dedicated to specific engine technologies are needed. Drive-train improvements associated with engine advancements involve automatic transmissions, continuously variable transmissions, automated manual transmissions, and dual-clutch transmissions.

Technology Status

All of these technologies are being actively developed today primarily in Japan, North America, and Europe. It is generally accepted in the industry that ICEs with conventional fuels will remain dominant for the next 10–15 years, mostly because of the advanced state of the technology. Diesel use is expected to grow (it is already 40% in Europe). Virtually all heavy-duty trucks are diesel-powered and more and more medium-duty trucks are as well. Diesel efficiencies are 40+% in a properly maintained engine. Fuel cells are a long-term option, probably well beyond 2020 or even 2030. Auto manufacturers are introducing hybrid-electric systems in light-duty trucks. Hybrids (the blending of various fuels and electric technologies) will become very significant in this timeframe. Fuel cells are not expected to make more than a niche penetration before 2020. By 2020, spark-ignited engines will combine the technologies mentioned above. A goal beyond 2020 is to reach a state of “zero emissions” with ICEs, which if achieved, effectively takes the automobile out of the environmental equation.

RD&D: Goals and Challenges

For spark-ignited engines, cylinder displacements need to be reduced up to 40% to achieve a corresponding benefit in efficiency. Fuel consumption for all types of engines needs to be reduced by 40%, carbon dioxide reduced up to 25%, light-duty diesel’s specific power output increased up to 70 kilowatt-liter, and new advanced NO_x and particle-removal technologies added.

The challenge for diesel engines is to improve fuel efficiency while meeting stringent emissions standards already in place in some parts of the world and likely to be imposed in others (e.g., China). Heavy-duty diesel engine improvements in sight are decreased fuel consumption with decreased NO_x and particulate emissions achieved by improving combustion with such options as flexible high-pressure injection, multi-valve cylinders, and boosting and electronic control. For emissions, lean NO_x traps and selective catalytic reduction based on urea plus an oxidation catalyst will be used. Fuel formulation is important to achieve this goal.

Commercialization and Deployment

The transportation industry expects these technologies to have moved from the research (basic and applied) stage to the development and demonstration stage by around 2020: advanced fuel-injection systems, variable-valve trains, hybrids, after-treatments, and transmission and drive-train improvements before then, with boosting, variable engines with combined combustion systems, but controlled auto-injection will follow. The strong coupling between efficiency and emissions (increasing one without harming the other), especially in diesel engines, is a significant barrier. Engine design options for decreased emissions typically involve a fuel economy penalty of as much as 20%.

Benefits and Costs

The benefits of these technologies are increased efficiency (perhaps doubling or more) and reduced emissions (perhaps 25% or more, eventually achieving 100%), including greenhouse-gas emissions. The benefits also include reduced dependence on oil. The U.S. government is spending over $100 million per year on alternative-fuel technology. On these technologies, and as in other areas, it is difficult to obtain an industry estimate. The costs are significant funds for RD&D, although the amounts are difficult to estimate a priori.

Risk Factors

- Technical—4: Risks appear to be low for many of these technologies as they are past the proof-of-concept stage. For diesel engines, achieving maximum efficiencies while decreasing emissions is a challenge.
- Commercial—2: Commercial risks seem low because these are for the most part evolutionary, and not revolutionary, changes in the basic transportation technology.
- Environmental—1: Although the technologies being discussed are designed to reduce emissions, there is always the possibility of unforeseen adverse effects.
- Regulatory—5: Ever-increasing environmental standards (NO_x, particulates, CO_2) could slow the introduction of a given technology. These standards may be a moving target with increasingly stringent regulations.

2. Alternative-Fuel Engine Systems

System Concepts

Alternative fuels are compressed and liquefied natural gas (CNG and LNG), ethanol (ETOH, usually from biomass such as corn or sugar cane), liquefied petroleum gas, diesel fuel from biomass, methanol, fatty acid methyl ester (FAME), and di-methyl ether (DME) (see Part III.D.5 for more discussion on the role of biofuels). Hydrogen is also an alternative fuel that can be used in ICEs, but it is the primary fuel for fuel-cell vehicles where it can more readily reach its maximum potential (see Part III.C.1). The use of blends of alternative fuels is being actively developed by the automobile and fuel industries.

Technology Description

Vehicles using alternative fuels are similar to today's vehicles in that they utilize an ICE. Some require upgraded fuel lines and fuel tanks, modified fuel injectors, and lubricants. Gaseous fuels require flow regulators. Among the concepts are flexible-fuel vehicles that are able to switch from one fuel to another on command.

Technology Status

The technology exists today to utilize these fuels. Prices are generally in the same range as conventional, gasoline-powered vehicles, with the exception of gas-fueled vehicles where the added equipment adds as much as $5,000 to the vehicle cost. Some automobile manufacturers have certified an alternatively fueled, ultra-low-emission vehicle for sale in several countries.

LPG motor fuel is the most commonly used alternative fuel (5.5 million vehicles in 1999 consuming 6% of global consumption of LPG). Ethanol is used mostly in the Brazil and the United States and CNG in Argentina and Italy. FAMEs are oils produced from vegetable matter and used as an additive to diesel fuel. If ETOH from biomass is used at concentrations up to 10%, only minor changes from the present technology are required.

RD&D: Goals and Challenges

The goal is to develop light- and heavy-duty vehicles to meet increasingly stringent emissions standards. The challenges are to meet cost, performance, and environmental objectives. Areas of concern are cost, range, and refueling convenience, and cold-start performance and engine efficiency (especially alcohol fuels). Most vehicles running on LPG are duel-fuel systems to compensate for the lack of LPG filling stations, and this in turn hinders the ability to maximize efficiency and minimize emissions. Ethanol results in improvements in CO and HC—carbon monoxide and (in this case) "unburned" hydrocarbon emissions, but when blended with gasoline, results in increased NO_x and evaporative emissions. The cost of ethanol, while having decreased dramatically since its early use in the 1970s, still remains above that of gasoline, even in Brazil where the raw material's (sugar cane) price is favorable (see Figure II-1). Further development of LPG vehicles is required to have this technology meet emissions standards, especially methane.

Commercialization and Deployment

Automobile manufacturers have produced alternative-fuel vehicles for some time. Brazil has run a large fraction of the vehicle fleet on ethanol for many years. Gasohol cars have been available in several countries since the late 1970s. Compressed natural gas buses have operated for at least this long. Prices for these vehicles are generally in the same range as their conventional counterparts. Thus, there is no general manufacturing impediment to mass use. Deployment of these vehicles will generally reduce emissions. This has and will continue to significantly impact urban air quality.

Risk Factors

- Technical—1-3: The technical risk is low, as all the technologies have been developed to at least some degree, although much work still remains. LPG is easy to use, but DME and methanol are more difficult and improvements are necessary (seals, pumps, etc.).
- Commercial—4: The commercial risk is not as low because it is not clear that consumers will move to alternative fuels, at least without government subsidies or mandates.
- Environmental—1: Because these fuels are superior to gasoline and diesel and have been developed with environmental factors in mind, the risk for the environment is essentially zero. With some of the fuels, there may be problems with some specific emissions (e.g., NO_x from ethanol, methane from CNG or LPG).
- Regulatory—1-9: The regulatory risk is problematic and is low in countries where specific fuels have already been introduced, but can be high where such steps have not been taken and where cost issues dominate environmental concerns.

3. Hybrid-Electric Power Systems

System Concepts

Hybrid Electric Vehicles (HEVs) use an electric motor to drive the wheels, either in parallel or series with a small on-board ICE.

Technology Description

Power can be supplied by small, high-efficiency units, including gas turbines, direct-injection diesel and spark-ignited ICEs, Stirling engines, and fuel cells (see Part III.C.2.)

Technology Status

Hybrid electric vehicles are commercially available in many countries, powered today by gasoline spark-ignition engines. Trucks are on the drawing boards of many companies and buses are in service today. Very efficient, clean diesel engines are available in some countries and are under very active development (see Part III.C.2). Advanced engine types such as the Stirling, free-piston, and advanced steam engines are also under development. The increasing power loads required by hybrid vehicles are aided by an integrated starter-generator able to deliver considerable power for the system (up 10 kW of generator power at 42 V). Automobile manufacturers are introducing hybrid-electric systems into light trucks.

The success of hybrid vehicles to date is owed to the advanced state of electric motor technology. Electric motors are efficient, powerful, and very controllable. It is expected that this technology will continue to improve.

Energy storage, particularly for hybrids, is currently in the form of electric and/or mechanical storage. Electricity is usually stored in lead-acid or nickel-metal hydride batteries. The specific energy in current batteries limits the range of all-electric vehicles (AEVs) but provides more than adequate motive power in hybrids. Hybrid-electric vehicles are believed by the industry to be very significant in the next 10–15 years.

RD&D: Goals and Challenges

- HEVs with 2–3 times the ~25% average efficiency of current vehicles (~25%).
- Advanced batteries and electricity storage devices with increased range and life cycles.

Commercialization and Deployment

HEV propulsion systems are in production at present by some manufacturers, operating on gasoline engines and in parallel mode. There has been a generally good public acceptance of these vehicles. The biggest competitor is the advanced ICE-powered vehicle. Whether consumers will pay more for a fuel-efficient vehicle is key. They are likely to demand more convenience to counterbalance any increased cost. For systems with gasoline as a fuel, no infrastructure changes will be necessary beyond what is available for ICE.

Benefits and Costs

The benefits of these technologies are more efficiency (perhaps doubling or more) and reduced emissions, including greenhouse-gas emissions. Depending on the particular technology, the benefits could be more or less.

Risk Factors

- Technical—6: There are a number of technical barriers (battery life, drive trains) that have to be overcome for these technologies to be competitive.
- Commercial—7: The markets for all of these technologies need to be developed. Continuing improvements in the ICE and drive trains of conventional motive power may impede hybrids' introduction into the marketplace.
- Environmental—3: These technologies in general will be friendlier to the environment by conserving fuel.
- Regulatory—4: Over-regulation (safety, economy) could impede progress.

4. Fuel-Cell Power Systems

System Concept

Fuel cells use hydrogen combined with oxygen to make electricity to drive motors. Hydrogen can also be used, although with lower efficiency, in conventional ICEs.

Technology Description

Fuel cells convert hydrogen directly to electricity in an electrochemical reaction. Their advantage in principal lies in the high efficiency of this conversion process (theoretically in excess of 70%, but practically less). Generally, fuel-cell vehicles may be twice as efficient as today's gasoline-powered vehicles and produce almost no emissions, other than water, depending on the base fuel to make the hydrogen. The hydrogen fuel can be stored on board or can be made on board using conventional liquid or gaseous fuels. The most advanced fuel cells for transportation, Proton Exchange Membrane (PEM), are in the demonstration phase today.

Technology Status

PEM fuel-cell vehicles are being tested in a number of markets in Japan, the United States, and Europe, but most scenarios have these vehicles making significant market penetration after 2020, and in many cases significantly after 2020. (The scenarios in Part II are in agreement with this assessment.) Fuel cells are a longer-term option for trucks and will likely be introduced in light trucks first. Also a long-term option, especially for trucks, is the solid-oxide fuel cell.

Two of the major challenges for fuel-cell vehicles are (1) carrying enough hydrogen onboard to provide adequate vehicle range, and (2) providing a convenient hydrogen refueling system [See also Part III.D, Reference 1, for the description of an international RD&D program (IPHE) to develop hydrogen fuel]. Hydrogen production is accomplished by centralized steam reforming of natural gas (or methanol) or by electrolysis. Reforming is the current economic choice. Distributed production is feasible but not yet operational and would have the advantage of producing hydrogen closer to its use, e.g., at a filling station, and utilizing the existing natural gas or electricity structure. Onboard vehicle production with a small natural-gas reformer has been examined by automobile companies over the past few years, but recently has seen less enthusiasm by automobile companies in favor of onboard hydrogen storage, either as liquid or as compressed gas (standard temperature or cryogenic). (A useful analysis of the problems associated with hydrogen can be found in Reference 5.)

RD&D: Goals and Challenges

- Fuel-cell stack systems with power density of 20 kW per liter in order to compete with the ICE, efficiencies of 60–70% at 25% peak power, rapid startup, and durability of 5,000 hours. Challenges are also system integration and packaging, cost and durability of components and CO poisoning of fuel cells, as well as reductions in weight, volume, and cost.
- Cost-effective, fleet-sized hydrogen reformers are needed to begin the transition. Effective sequestration of the CO_2 produced by this method is a major technical and economic challenge. In the longer term, high-temperature electrolysis has potential, as does thermo–chemical cycles that directly convert hydrocarbons to hydrogen, if costs can be reduced most likely through efficiency improvements using advanced technologies.

Commercialization and Development

Almost all automobile manufacturers are pursuing fuel-cell development, mostly centered on PEM fuel cells that operate at relatively low temperatures. The major other type of fuel cell suitable for vehicles (high power density) is the solid-oxide fuel cell (SOFC) but that operates at a much higher temperature. Manufacturability and cost are the most significant issues. While size and weight are coming down, they are still substantive issues. In principal, fuel-cell vehicles can combine zero emissions as in the AEV with the range of conventional vehicles (**Figure III-25**). This technology lags both AEVs and HEVs, and thus requires longer lead times and larger investments. Fuel cells other than PEM are even further behind in development, especially for vehicles. Based on the prices paid for stationary and motive power, fuel cells would be expected to penetrate the stationary market first and the technology development to be followed closely by the transportation sector (see Part III.D.1). There are indications, however, that each sector is closely watching and expecting to follow the lead of the other.

Figure III-25. Examples of Fuel-Cell Hybrid Vehicles.

The technology for using fuel cells in reversible mode, that is making electricity by turning hydrogen and oxygen into water or using electricity to turn water into hydrogen and oxygen, is intriguing. The technology envisions vehicles that use solar or grid electricity, making and storing the fuel on board to power the vehicle on demand. Fuel cells in vehicles are also envisioned to possibly power a home when the occupant is not driving the vehicle.

One of the key issues surrounding the development and deployment of fuel-cell vehicles, and to some extent HEVs, is the price and availability of hydrogen fuel. As stated, most manufacturers have abandoned onboard reforming of liquid fuel in favor of gaseous hydrogen, compressed and possibly cryogenic. Critics of hydrogen cite cost, safety, and lack of infrastructure as severe hindrances to the commercialization of hydrogen-fueled vehicles (see References 3 and 5).

<u>Benefits and Costs</u>

The benefits of these technologies are more efficiency (perhaps doubling or more) and reduced emissions, including greenhouse-gas emissions. Depending on the particular technology, the benefits could be more or less. To begin with, it is very difficult to obtain even estimates of the expenditures on these technologies today. A few years ago, U.S. government expenditures in this area were on the order of $100 million per year. Industry investments in the United States, much less the entire globe, are almost impossible to obtain due to competitive forces.

Clearly, the time to bring any of these technologies to market, assuming that technical progress more or less continues at the same rate, depends on the rate of investment. Based on annual U.S. government R&D expenditures alone, the amount is likely to be in the billions of dollars or euros per year at a minimum, and possibly in the tens of billions. The World Business Council paper argues for government support of basic and pre-competitive applied research to advance these technologies.

<u>Risk Factors</u>

- Technical—6: There are a number of technical barriers (fuel-cell energy densities, sufficient compact hydrogen storage) that have to be overcome for these technologies to be competitive.
- Commercial—7: The markets for these technologies need to be developed.
- Environmental—3: This technology should be friendlier to the environment.
- Regulatory—4: Over-regulation (safety, economy) could impede progress.

5. Other Power Systems

This section includes electric and turbine propulsion. (A useful reference for the status of the technologies discussed here and their expected direction can be found in Reference 6.) High-speed air travel is one of the fastest growing components of the transportation sector.[7] The stable price of electricity has fostered the growth, in high-population density countries, of high-speed rail (see Reference 1).

System Concepts

AEVs use a rechargeable energy-storage system (battery, flywheel, ultracapacitor) to supply power to electric drive wheels.

New concepts of turbines include advanced jet aircraft with higher turbo-fan bypass ratios, increased-cycle pressure ratios, higher turbine inlet pressures, improved turbine aerodynamics, reduced unloaded weight, and fuel systems utilizing hydrogen. Because of its low weight, advanced aircraft is the likely first use of hydrogen fuel for air transport. Supersonic transports (SSTs) are a long-range option.

High-speed rail (HSR) include coaches on steel rails or very-high-speed rail using magnetic levitation (maglev).

Technology Description

The drive system in AEVs receives energy from on-board energy storage devices. These storage devices must be charged by either connecting to the electrical grid or to some other source of electricity (fuel cell, solar PV panel, generator). AEVs use a combination of technologies and are capable of utilization with a variety of energy storage methods.

Ultra-high-bypass turbofans, and prop fans with counter-rotating prop designs are available for airplanes.

Existing HSR systems require electrified railways such as the French TGV, the Japanese Nozomi, and the German Inter-City Express. Speeds attained are up to 320 kilometers per hour. Existing maglev systems are still in the trial stage and include the Japanese Linear Motor Express and the German Transrapid.

Technology Status

The specific energy in current batteries limits the range of AEVs. The aircraft industry (Boeing, Airbus, GE, and Pratt & Whitney) is actively pursuing research in all of the high-speed air technologies. For the more advanced concepts, government agencies (e.g., NASA in the United States) are also involved.

HSR is a mature technology with Italy and Spain involved as well as those already mentioned. Maglev is still a very expensive technology.

RD&D: Goals and Challenges

- Every percent reduction in airplane weight reduces fuel consumption by up to 0.5%. Goal is to achieve a 40% efficiency improvement in 20 years from a combination of engine improvements and drag and weight reductions. The development of a laminar flow technology will greatly assist in this goal.
- Improve maglev systems and technology. Develop room-temperature maglev to avoid expensive cooling costs.

Commercialization and Deployment

Some manufacturers have leased AEVs to private individuals; however, consumer leases have been less than anticipated. The major problem with AEVs has been the range of these vehicles, and like HEVs, there is some concern about whether sales can ever be high enough to reduce consumer costs to the level where sales are not inhibited. The industry is still searching for that point. The competitors for the AEV are the advanced ICE-powered vehicle and the HEV. HEVs will in all likelihood have lower emissions.

Airplanes are being improved by industry. Maglev trains exist on small commercial routes but more pilot projects are needed. Room-temperature maglev technology exists but requires more development.

Benefits and Costs

The benefits of AVEs are reduced emissions although there are still emissions at a fossil-fuel power source. A 40% efficiency improvement in aircraft will result in a savings of almost 3 million barrels of oil per day in 15 years.[8] A 50% increase in overall efficiency of rail transportation would save about the same amount of energy.

Risk Factors

- Technical—2: Much of the technology needed is past the basic research stage and into applied research to reduce costs and improve efficiency.
- Commercial—6: Because the market is limited, the commercial risks are above normal.
- Environmental—4: While electrified railways are environmentally friendly, the effects of high-speed air transport, especially with fossil fuels, are little known. Hydrogen fuel, while fundamentally benign, will introduce additional water vapor into the upper atmosphere with unknown consequences.
- Regulatory—2: Although new technologies are being introduced, industry works closely with government agencies.

6. Summary

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

A more detailed study, specifically looking at the deployment of new transportation technologies, their time frames and locations, should be performed so that both industry and governments can appropriately plan for this very important energy end-use sector.

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8. *International Energy Outlook*, Energy Information Agency, U.S. Department of Energy, http://www.eia.doe.gov/oiaf/ieo/index.html, 2002.

D. Crosscutting Technologies

Crosscutting technologies are those that have the potential to broadly and significantly affect the end-use of energy, rather than concentrated in one sector. They may or may not be energy technologies in and of themselves. Perhaps the best example is fuel cells, an energy technology that may prove useful for both stationary and mobile applications. Examples of general crosscutting technologies that have uses more broadly in society are nanotechnology, biotechnology, information technology, automation, and the transmission, distribution, and storage of forms of energy.

1. Fuel Cells

A fuel-cell power plant typically consists of two or three parts:

1. A processor to convert hydrocarbon fuel or electricity to hydrogen.
2. The fuel cell itself in the form of stacks of individual cells.
3. A power conditioner to convert direct current to regulated alternating current for stationary use.

A number of useful documents and sites can be accessed to find more information on these and associated technologies.[1] (See also Part III.B, References 21 and 22.)

Polymer electrolyte (Proton Exchange Membrane, or PEM), phosphoric acid, solid-oxide, and molten carbonate are common types of fuel cells in use or under development. Large fuel cells producing up to several megawatts are well into the demonstration phase. Systems producing 100 to 200 kW are being used in heavy transportation (buses) and in smaller industrial and residential applications (see Part III.B.2).

About 160 phosphoric-acid fuel-cell plants on the scale of 100–200 kW are in use worldwide. Molten-carbonate fuel cells and solid-oxide fuel cells have been tested in several countries so far. PEM fuel cells are promising for automobiles due to their very-high-specific energy density and low-temperature operation (see Part III.C.4). However, many technical barriers have to be overcome before commercialization. Industries in the United States, Europe, and Japan are investing significant resources in developing commercial products.

Phosphoric-acid fuel cells have demonstrated their technical performance in several countries (United States, Germany, Japan, Korea, India, and Taiwan) with ratings from 50 kW to several megawatts. However, cost-competitiveness in the marketplace has not been achieved. Second-generation, molten-carbonate fuel cells have been introduced in the United States, The Netherlands, Germany, Denmark, Spain, Italy, Korea, and Japan. They feature high-energy efficiency and utilize waste heat. Third-generation, 100–1,000-kW, solid-oxide fuel cells have been demonstrated in the United States, The Netherlands, Germany, Switzerland, and Japan. Associated with their high-temperature operation is small-scale cogeneration of power on a scale of tens of megawatts.

The challenges to the further development and marketing of fuel cells for transportation include—

1. Reducing costs through the development of key materials,
2. Developing small-scale reformers, and
3. Developing compact, onboard storage systems for hydrogen.

The target level is cost-competitiveness of these systems with conventional liquid-fuel based systems.

When will fuel cells become cost-competitive? The price of fuel cells must drop from the present $10,000 per kW to around $3,000 per kW for remote stationary power, $1,000 per kW for grid-power systems, and $100–300 per kW for automobiles. Utility generation systems now cost up to $2,000–3,000 per kW. Automotive systems have to be one-hundredth of their current cost to compete with advanced diesel and gasoline engines in hybrid configurations. Automotive systems should have 50–70% efficiency, no regulated emissions, and a 5,000-hour lifetime, while stationary systems should have a 40,000-hour lifetime. Small fuel-cell systems are eventually expected to enter the home, commercial building, and industrial markets, and small units are being deployed in developing countries for remote, stationary power operations. Where power costs can be as high as $5,000 per kW, a sub-class of fuel cells called mini- or micro-fuel cells is being developed for portable power. Applications for mini and micro-fuel cells include mobile telephones, laptop computers, power tools, and medical applications.

In any future market penetration, CO_2 reduction and urban air pollution reduction are benefits, if hydrogen fuel can be made without releasing CO_2 into the atmosphere. The advantages and motivation of a hydrogen economy essentially depend on hydrogen production costs and the efficiency at which this fuel can be utilized. Government incentives can be beneficial to the introduction of this technology. The International Partnership for the Hydrogen Economy (IPHE) is an international cooperative program of advancing RD&D on hydrogen and fuel cells across the application spectrum with the goal of making the hydrogen economy a reality.[2]

Generally speaking, since the return on R&D investment may be long, i.e., more than 10 years, governments will have to shoulder a significant portion of the R&D costs until industry can foresee a return on investment and proceed to the demonstration phase.

2. Transmission and Distribution

Electricity and natural-gas transmission and distribution (T&D) technologies are the means by which the benefits of energy are made available to customers, the end-users of energy. With the electricity blackouts in the summer of 2003 on the east coast of the United States and Canada, and later in Sweden and Denmark, and then in Italy, electricity transmission networks revealed their vulnerability. Energy losses in the U.S. electric T&D system were 7.2% in 1995, accounting for 2.55 EJ. In Japan, the figures were 5.4% in

2002. Worldwide electricity T&D losses totaled 1,333 TWh (14.1 EJ) in 1999, or 11.6% of global electricity consumption. T&D losses account for 7.4% of electricity consumption in OECD countries and 13.4% in developing countries.

Technology Description and Status

Power Systems. The knowledge-based economy of the future will require a "smart power" delivery system that links information technology with energy delivery. The concept of the smart power delivery system includes automated capabilities to recognize problems, find solutions, and optimize the performance of the power delivery system. The basic tools include advanced sensors, data processing and pattern recognition software, and solid-state power-flow controllers to reduce congestion, react in real-time to disturbances, and redirect the flow of power as needed. There are three primary objectives:

- **Optimize the overall performance and resilience of the system.** An array of sensors will monitor the electrical characteristics of the system (voltage, current, frequency, harmonics, etc.) as well as the condition of critical components, such as transformers, feeders, circuit breakers, etc. The system will constantly fine-tune itself to an optimal state, while constantly monitoring potential problems that could disturb it. When a potential problem is detected and identified, its severity and the resulting consequences are assessed, corrective actions are then identified, and the effectiveness of each action is assessed. The operator can then implement the corrective action very efficiently by taking advantage of the grid's automated control features.
- **Instantly respond to disturbances to minimize impact.** When an unanticipated disturbance does take place, it is quickly detected and identified. An intelligent "island" or sectional scheme, for example, can be activated instantaneously to separate the system into self-sustaining parts to maintain electricity supply for consumers according to specified priorities and to prevent blackouts from propagating.
- **Restore the system after a disturbance.** Following the system's reaction to a major disturbance, actions are taken to move the system toward a stable, operating regime. To do so, the state and topology of the system need to be monitored and assessed in real time, allowing alternative corrective actions to be identified and the effectiveness of each determined by look-ahead computer simulations. The most effective actions are then implemented automatically. When a stable operating state is achieved, the system again starts to self-optimize.

When a disturbance occurs, the operating objective moves from reacting to restoring and finally back to optimizing. The smart power delivery system is thus said to be "self-healing." Some of the key technologies that will be needed to implement a smart, self-healing grid are—

- **Solid-state, power-flow controllers.** By acting quickly enough to provide real-time control, solid-state power-flow controllers—such as FACTS and Custom Power devices—can increase or decrease power flow on specific lines, alleviating system congestion. In addition, these controllers enhance system reliability by counteracting transient disturbances almost instantaneously, allowing the system to operate closer to its thermal limits.

- **Anticipation of failures and disruptions.** Substantial work has been done by EPRI and others in determining the root cause of failures in critical components, such as transformers, cables, surge arrestors, etc., and in developing monitoring and diagnostics systems for these components. The next step is to develop fault-anticipation technology that provides early warning and forecasts failures.
- **Adaptive islands.** Following a terrorist attack or a major grid disruption from natural causes, initial reaction focuses on creating self-sufficient islands in the power grid, adapted to make best use of the network resources still available. To achieve this aim, new methods of intelligent screening and pattern extraction are needed, which rapidly identify the consequences of various island reconnections. Adaptive load forecasting is also used to dispatch distributed and other resources in anticipation of section reconnection and to help stabilize the overall T&D system.
- **Real-time, wide-area monitoring system.** Elements of the real-time wide-area monitoring system are already in operation on both the transmission and distribution system. For example, Wide-Area Measurement System (WAMS), originally developed by the Bonneville Power Administration, is a system based on high-speed monitoring of a set of measurement points and the generating of displays based on these measurements. WAMS provides a strong foundation on which to build the real-time, wide-area monitoring system required for the self-healing grid.
- **Wide-area control systems.** Once predictions have been made about the effectiveness of various potential control actions, the identified actions need to be carried out quickly and effectively. Achieving this goal will require automating many operations that will make human intervention on both transmission and distribution systems more efficient. The challenge is to develop new equipment with the required intelligence while also developing strategies for retrofits to existing equipment.

Despite the promise of the future of power delivery technologies, the current reality is that delivery systems throughout the developed world cannot satisfy the increasing complexity of the market place or the increasing digital needs of the 21st century. Meeting the requirements of the future will require substantial upgrades in three broad categories:

- Continuing to build for load growth and replacement of aging assets;
- Correcting deficiencies in the power delivery system and bringing it up to historical levels of reliability; additional investment is needed to make up for reduced expenditures in recent years;
- Transforming the existing infrastructure into a smart power system, with greater functionality for consumers, and with the ability to reliably support the digital society of the future.

These three categories can be used to estimate costs for both transmission and distribution upgrades. Importantly, the total cost of transforming the grid is not equal to the sum of the costs for load growth, deficiency corrections, and system transformation. In fact, the marginal cost of transformation is substantially less than the sum of the individual components. This is because many of the tasks in the first two categories can be performed in a way that also addresses the needs for system transformation. These cost-reduction “synergies” have the potential to reduce overall costs of transmission and distribution by 30% or more.

Important technologies include HVAC (high-voltage alternating current) and HVDC (high-voltage direct current) transmission, high-efficiency transformers and real-time system controls to improve dispatch, superconductive rotational machines, HTS (high-temperature superconducting) cables and power transformers, better core materials and winding designs of transformers, real-time controls, and wide-area measurement capabilities to analyze grid disturbances in real time.

HVDC transmission systems have the potential to operate over very long distances (>2,000 km). Today, the longest HVDC transmission is between northern Quebec, Canada, and New England in the United States (1,486 km). International electricity export and import over long distances (>2,000 km) will be done in the future only by HVDC. Long-distance HVDC lines or submarine transmission are a distinct advantage in terms of system stability due to the high impedance of cable. Even though the advantages of HVDC over those of HVAC are most pronounced for longer distances, ABB has developed a version that appears to be economic even over shorter distances.

There are many HVDC installations throughout the world (**Figure III-26**). One unique feature of HVDC is the asynchronous connection of two HVAC electric systems operating at different frequencies, for example between 50-Hz systems and 60-Hz systems, connected through DC. Conventional power devices (e.g., rectifiers) using HVDC is a mature commercial niche product with a 30-GW installation in North America. The potential market in China and India is very large at 100 GW. R&D goals include an HVDC voltage-source converter terminal that costs one-half of current models.

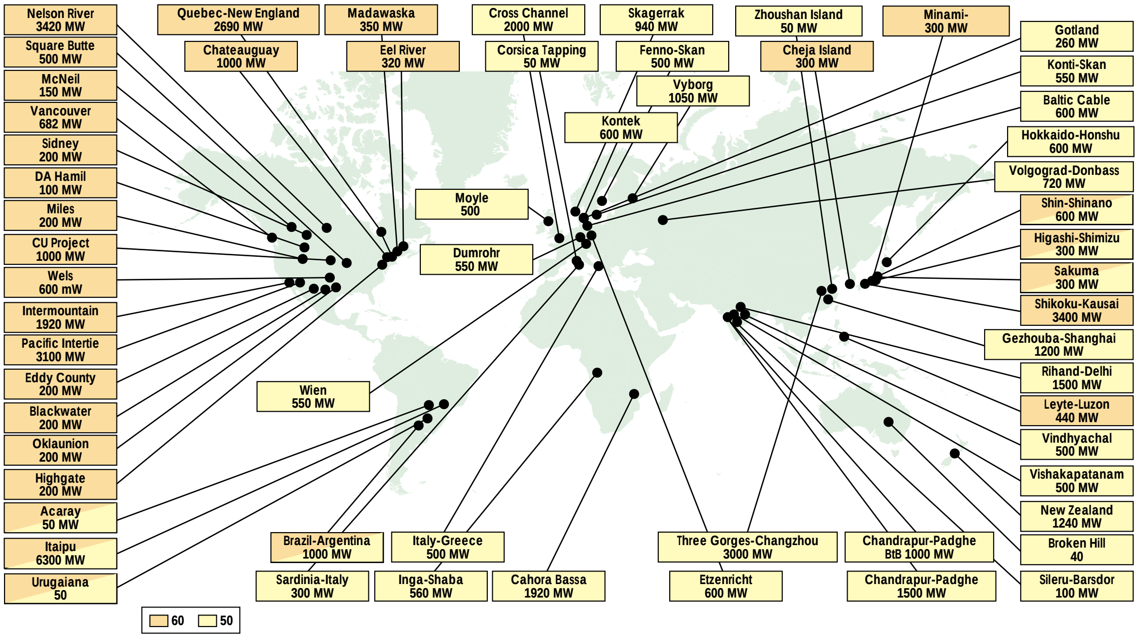


Figure III-26. In-service HVDC transmission in the world, 2001 (Source: http://www.cigre.org).

HTS cables will modernize the urban electricity networks by replacing conventional cables. Very densely populated areas, such as Tokyo and New York, with very limited rights of way for transmission systems, require the refurbishment of existing systems. HTS cables have practically no resistance loss. Currently, 5–10% power is inevitably lost through conventional transmission conductors. The United States, France, Denmark, and Japan have had demonstration projects using HTS cables. A project in Copenhagen in 2001 marked the first commercial grid application of HTS cable. A Japanese project featured the longest line of cable at 100 m with 66 kV. A Japanese HTS power transformer has a capacity of 1 MW. However, because conventional power transformers already operate at 99.80% efficiency, it is not clear that this specific technology is needed. There are still many technical barriers to commercializing HTS cable. Low-loss transformer core materials have been offered in the United States and Japan for over 15 years, but sales have been declining in the U.S. and manufacturers are leaving the market as purchasers move to conventional lower-cost, lower-efficiency transformers.

R&D goals are HTS cables capable of current densities $>10^6$ amps per cm^2 in kilometer lengths and at a cost of less than 10% of current materials, and transformer steel costs reduced by 50%. R&D on HTS was conducted in the United States at the level of about $19 million in 1997. Of this amount, $12 million can be roughly attributed to HTS T&D. Improved HTS materials and reduced manufacturing costs are critical areas for R&D. A need for R&D in general in this area is the reduction of artificial neural net training requirements by a factor of 10.

<u>Risk</u>

In terms of risk, because HVDC is commercial technology and has many applications worldwide, the technical risk is very low. HTS cable, on the other hand, is still in the demonstration phase and no long-distance transmission (over 100 m) has yet been demonstrated. The development of cable and junction boxes and peripherals is required. In this sense, the technical risk for HTS transmission is relatively high.

HVDC by overhead transmission might have potential environmental risks of DC/voltage EMFs (electromagnetic fields) upon human health. This is a very controversial issue and there is no consensus scientifically or politically. Therefore, the environmental risk is high. HTS cable systems employ cryogenic media and since the long-distance installation of such cables and their associated cooling systems has not been evaluated, the environmental risk is high. HVDC technologies are proven and used worldwide with regulatory permissions and clearances, and therefore the regulatory risk seems to be very low. In consideration of technology status of HTS cable, the regulatory risk is moderate or high.

HVDC technology is sustained by a limited number of suppliers such as Siemens, ABB, GE, Alsthom, Hitachi, Toshiba, and Mitsubishi and the next-generation systems will likely be developed by this industry. HTS cable has been developed partly by cable industries worldwide, but its major impact is still many years away. However, the high potential for the next-generation of urban distribution systems warrants continued government support of R&D, if the technology is to be utilized as soon as possible.

Natural Gas

Natural-gas distribution systems have not had major outages but rather limited disruptions due mostly to failures from unexpected breaks. Potential explosions are a major concern and studies of system vulnerabilities are among the lead areas needing R&D, followed by fundamental studies of the chemistry and handling of gases. An insight into R&D activities in natural gas T&D may be found on the Gas Technology Institute website.[3] Specific technologies under study include advanced gas-flow meters, methods to assess pipeline corrosion, the detection of stress-corrosion cracks in the operating pipeline, and detection of gas leaks from a distance.

The principal issues associated with the expanded use of natural gas for electricity generation are the use, transport, and regasification of liquefied natural gas (LNG). LNG terminals appear to be necessary if advantage is to be taken of a global energy resource that may be oceans away from the end-uses.

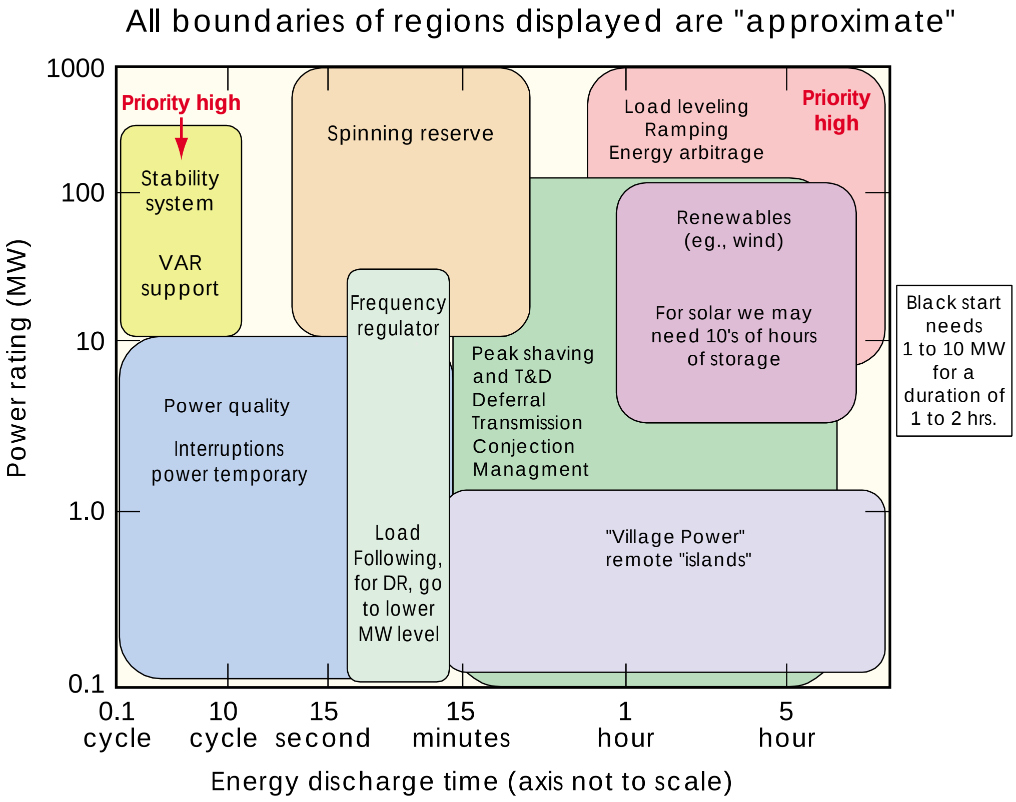
3. Energy Storage

Advanced energy-storage systems include mechanical (flywheels, pneumatic), electrochemical (advanced batteries, reversible fuel cells, hydrogen), purely electric or magnetic (ultracapacitors, superconducting magnetic storage), pumped-water (hydro) storage, and compressed-gas (air) storage. The various demands for electricity storage shown in **Figure III-27** illustrate the complexity of the requirements for energy storage for different purposes.

Adding any of these storage systems necessarily decreases the energy efficiency of the entire system because of the conversion efficiencies in both input and output. While typically high, these efficiencies are nevertheless multiplicative. The main advantage of energy storage is to balance loads and enable and enhance the use of energy sources that generate electricity during times of weak demand, such as base-load nuclear power plants, and to level out fluctuations in other sources, such as wind and solar photovoltaic systems (**Figure III-28**). In vehicles, this allows much of the kinetic energy to be recaptured and facilitates electric drive trains. The year 2003 marked yet another recognition of the importance of electricity storage with the electricity blackouts on both sides of the Atlantic.

The mechanical storage of energy in flywheels is very old. The most important factor is how to reduce energy loss in the mechanical bearings supporting the flywheel. Vehicles require energy storage of 10–20 Wh per kg of weight of the flywheel and power densities of 2 kW per kg and have a high life cycle (10^5 cycles). Requirements for utilities or homes vary, but need to be in the tens to thousands of megawatt-hours.

Electrochemical energy storage utilizes chemical reactions to store electrons in a battery. Batteries include the classic lead-acid battery, the zinc-bromide battery, zinc-chloride battery, redox flow battery, and sodium-sulfur battery. Reversible fuel cells are a type of electrochemical battery that, when turned on, can work either to yield electricity from hydrogen and oxygen or yield hydrogen (and oxygen) from electricity (an electrolyzer).



(Prepared by Attendees at EPRI Energy Storage Think Tank, July 11-12, 2002)

Figure III-27. Power and discharge time requirements for energy-storage systems. Highest priority items are marked, as is the startup from a complete system blackout. All boundaries of regions displayed are approximate. (Source: Electric Power Research Institute, 2002).

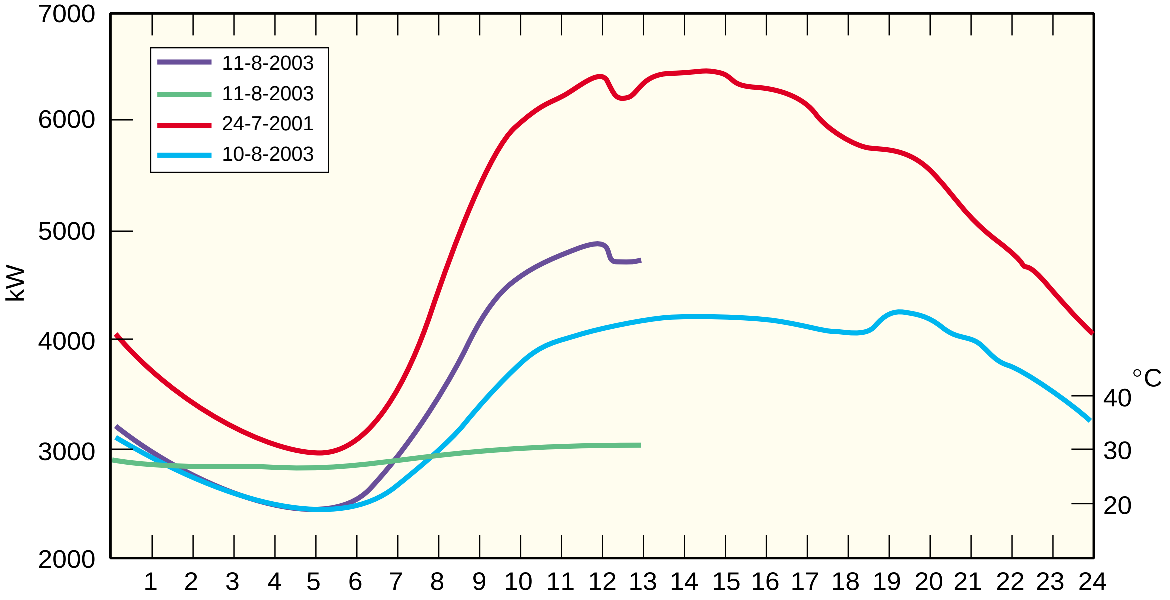


Figure III-28. Daily load curve of Tokyo Electric Power. Red: highest demand of the past (blue: 1st day, light blue: 2nd day, green: 1st day temperature).

Ultracapacitors are capable of very-high-energy density in terms of mass and weight and utilize very strong dielectric materials. Superconducting magnetic energy storage (SMES) uses persistent current running in superconducting magnets. Energy input and output is accomplished through AC-to-DC converters with rapid response (milliseconds). The general status of these technologies is shown in **Table III-8**.

General goals for every type of energy storage is high reliability, over 85% efficiency, and per-kilowatt costs less than or equal to those of new power generation ($400–600 per kW). The major hurdle for all storage technologies is cost reduction. Superconducting cable design for stability and low loss is an important research area for existing superconductors. HTS cables that carry high currents could reduce both capital and operating costs for SMES. For electricity storage devices linked to distribution or transmission grids, power electronics interfaces represent a sizable share of the total cost of electricty storage.

Flywheels require further development of failsafe designs and lightweight containment as well as scaling up the size and advancing the superconducting magnetic bearings. Magnetic bearings could reduce parasitic loads and make flywheels attractive for small, uninterruptible power supplies and as a player in home cogeneration systems. Ultracapacitor development requires improved energy density from the current 2 Wh per kg for light-duty hybrid vehicles. Advanced higher-power batteries for vehicles with greater energy-storage capacity and longer cycle lives are necessary before significant market penetration. As for utilities application, cost reduction is essential, even though some advanced batteries like sodium-sulfur have already penetrated the market in Japan with accomplishment of 1,500 cycle lives.

Generally speaking, for utility energy-storage applications, only pumped hydro storage has made significant market penetration globally. The largest plant is 2,100 MW. The number of pumped hydro plants of over 1,000 MW is 30 in the world. There is much small-scale prototype development work in SMES in the United States, Germany, Russia, and Japan. On the other hand, micro-SMES developed by ASC (American Superconductivity Co.) has been connected to the grid in South Africa (ESKOM), and at

Table III-8. Technology status of various energy storage options (Source: modified from Technology Opportunities To Reduce U.S. Greenhouse Gas Emissions, http://www.ornl.gov/climate_change, 1997).

Technology	Efficiency (%)	Energy Density (Wh/kg)	Power Density (kW/kg)	Size (MWh)
Stationary				
Pumped Hydro	75	0.27	low	$5\text{-}20 \bullet 10^3$
Compressed Gas	75	N/A	low	$0.2\text{-}2 \bullet 10^3$
SMES	>90	N/A	high	10^3
Mobile				
Batteries	70–84	30–50	0.2–0.4	17–40
Flywheels	90+	15–30	1–3	0.1–2.0
Ultracapacitors	90+	2–10	0.5–2	0.1–0.5

Carolina Power and Light and Wisconsin Public Service in the United States. Advanced power batteries are still in the demonstration stage except for the sodium-sulfur battery in Japan. There have been installations of tens of units of megawatt-scale, sodium-sulfur batteries in Japan and one test bench at the Research Center of American Electric Power in Columbus in the United States. If energy-storage devices and equipment can become cost-competitive with existing power generation facilities in terms of dollars per kilowatt, then there is an enormous market potential.

Steel flywheel systems operating at comparatively low speeds are available commercially and back up grid electric power during planned outages or unplanned disturbances where power quality is critical. Applications include Internet data centers, semiconductor manufacturing plants, and data processing (e.g., banking). Flywheels using advanced materials such as composites have several important technical barriers to overcome such as material deformation, superconducting material development, stable control methodology, development of the rotation axis, a reliable emergency shutdown, and safety. Therefore, the technical risk is very high. Some of advanced batteries have been put into actual service, especially in Japan. Technical risk for the sodium-sulfur battery is low. Overall risks of this technology including other types of advanced batteries are moderate. Some bench-scale demonstration projects have shown good performance of SMES. However, it is necessary to confirm the same performance with commercial-scale machines and therefore the technical risk is fairly high.

All types of storage technology will have a huge market potential once the technical risks are overcome and costs are reduced. Therefore, commercial risk is relatively low. It is too early to say what the environmental risks are although they should be low. Only batteries present a potential risk from chemical production and disposal. It is also much too early to speculate on regulatory risk, although with any new technology, regulatory hurdles may be high.

In terms of government versus industry participation in R&D, except for some advanced batteries like sodium-sulfur, other energy-storage systems, especially for utility-scale applications, need extensive R&D to let the marketplace choose. Based on research activities by the private sector, partly supported by governments in the United States, Japan, and Germany, it is still necessary to support long-term development with government funds, as well as to promote international cooperation of research activities.

4. Nanotechnology and Advanced Materials

The remarkable expansion in the capability of computers and other electronic devices over the last few decades has been enabled by microminiaturization more than any other single factor. Makers of integrated circuits are locked into fierce competition to put more and more transistors on smaller slices of silicon, enabling electronic products with greater power, speed, connectivity, and portability for a public that has come to expect continuous electronics innovation. These micron-scale chip structures, a thousand of which could be lined up side by side on the head of a pin, are nonetheless behemoths compared to the yet thousand-times-smaller nanodevices being conceived in the next miniaturization push. All of these applications will rely on high-quality power, and the smart power system described earlier to provide it.

Nanotechnology operates on the scale of individual molecules and atoms—the basic building blocks of matter—and is concerned with creating materials and systems that have electrical, chemical, mechanical, or optical properties that are superior to their larger counterparts. By learning how to handle and assemble the appropriate atomic and molecular building blocks, nanotechnologists hope to develop materials and functional devices unlike any now in existence. The possibilities range from catalysts with hugely increased surface areas to minuscule machines having real levers, gears, and motors. The new capabilities expected from working at nanoscale are not just the result of orders-of-magnitude size reduction but of the possibility of discovering and utilizing genuinely new phenomena that appear only at the atomic level.

Exciting Opportunities

A typical macroscopic structure contains groups of many trillions of molecules. Nanotechnology, in contrast, involves groups of a few or even single molecules. This difference is fundamental to the ways that materials in each size regime respond to their environments. Major differences between the behaviors of nanostructures and conventional materials result from the much larger surface area per unit volume and confinement effects within nanostructured materials. Because many important chemical and physical interactions are governed by surfaces, a nanostructured material can have substantially different properties from those of a macroscopic material with the same composition. Compared with conventional materials, nanostructured substances can display extraordinary differences in rates and control of chemical reactions, electrical conductivity, magnetic properties, thermal conductivity, strength, ductility, and resistance to fracture. The broad outlines of these differences are known or anticipated,[4] and they suggest a great number of possible applications in a wide variety of disciplines.[5] Selected examples of nanotechnology advances follow with emphasis on applications relevant to the needs of the power system.

Power System Applications

Advances in nanomaterials are expected to be especially valuable in power system applications, from superstrong metal alloys for rotating machinery to tough composites that resist corrosion attack, less-brittle ceramics for power line insulators, and slick coatings that will reduce biofouling in cooling water intakes. Nanoscale research on lattice structures and electron pairing are expected to improve our understanding of superconductivity, leading to new alloy formulations, novel fabrication techniques, and hopefully a material that will superconduct at room temperature. Other research is looking into using nanotechnology in the remediation of environmental problems, in the development of “green” processing technologies, and for nuclear waste management systems (see Reference 5).

Hydrogen is the ideal feedstock for fuel cells (see Part III.D.1). While progress in the development of catalysts for internally converting methane to hydrogen has reduced operating temperatures for some fuel cells to the 300–400°C range,[6] advanced nanostructural catalysts may allow hydrocarbon reforming at very low temperatures (below 100°C). Successful development of such catalysts would help substantially in making fuel cells that operate at ambient temperatures.

Applications in advanced power-generation technologies are also foreseen. The catalysts mentioned above should have direct use in improving the performance of fuel cells, which are just now becoming commercially viable. Hybrid photovoltaic solar cells based on conducting polymers and semiconductor nanorods also hold special promise; by combining the excellent electronic properties of inorganic semiconductors with the process flexibility of organic polymers, researchers are homing in on PV devices with good efficiencies that are easier and much less expensive to manufacture than conventional solar cells. Early prototypes have demonstrated power conversion efficiencies approaching 8% in the laboratory, a level expected to be improved significantly through engineering refinement and new material formulations.

Brand new generation options may also become feasible with the advent of new nanomaterials. Magnetohydrodynamic (MHD) generators, which produce electricity by passing a very hot, ionized gas through a magnetic field, have been stymied in the development stage by the insufficient durability of system components—especially the electrodes, which tend to corrode badly under the high temperatures involved. Tougher materials specially engineered for this application may reopen the investigation of MHD, which could be used in a combined-cycle configuration with a conventional steam turbine.

Electronics Applications

Application of nanotechnology in electronics is not so much a matter of opening up new, practical capabilities but of finding ways to do what we are doing now faster, cheaper, and with a smaller footprint. Nanotechnology made a big score in the late 1990s with IBM's commercialization of the giant magnetoresistive head—an enabling sensor technology that gave a tremendous efficiency boost to the high-density data storage industry.[7] Memory and storage will continue to be a primary focus for nanotechnology applications, with research proceeding on approaches centered around single-electron tunneling, resonant tunneling diodes, and electron spin effects. In other research, two- and three-dimensional arrays of magnetic nanoparticles crystallized out of a colloidal suspension appear to offer storage capability 10 to 100 times greater than that of present memory devices.[8]

This packing of more and more memory into a tiny space is one key to making electronic components smaller, more versatile, and less expensive—characteristics that continue to drive the proliferation of consumer electronics. The shrinking size and cost of electronic components are now not only increasing the "unnoticed" use of embedded microprocessors in all kinds of products—a new car might have as many as 70—but are also making possible the convergence of many discrete gadgets into small, multifunctional appliances that combine the capabilities of telephones, pagers, PDAs, cameras, global positioning systems, and Internet browsers.

In essence, the challenge for electronics applications boils down to finding ways to extend the run of Moore's Law, which says that the number of transistors that can be squeezed into an integrated circuit doubles about every 18 months. Some experts think Moore's Law will be broken within the next 15 years, as computer chips approach fundamental limits to current methods of manufacture. The size of microelectronic components has already dipped down below the micron level and currently stands closer to 100 nm. Continuing beyond this threshold looks to be much more complicated and vastly more expensive than in the past. While nanotechnology would seem to be just what is needed to solve this problem, success is far from assured for the reasons explained below.

Critical Capability Gaps

Fabrication problems. Making actual microscale circuits can be done—several types of transistors, the building blocks of most integrated circuits, have already been constructed from organic molecules and from carbon.[9] The real problem is in finding ways to mass-produce them at low cost, as microscale circuits are today. Microelectronics in current equipment are fabricated by photolithography, basically the same technique used to make circuit boards in 1950s-era portable radios. In photolithography, a mask that delineates the pattern of the circuit is created and reduced in size photographically; a beam of light shines through the mask and focuses on a silicon wafer coated with a photoresist layer. The illuminated areas (the areas not masked out) can be selectively removed in a chemical etching process, and what remains is a tiny replica, in silicon, of the original circuit pattern (see Reference 8). Such a process is perfect for mass-production.

Unfortunately, at the nanoscale, the wavelength of the light used in the process—even the shortest wavelengths of ultraviolet—is larger than the details desired for the circuit itself, causing extreme diffraction effects and a blurry result. While the use of x-rays and electrons instead of light has been investigated, these substitutions carry their own technical difficulties. So-called "soft" lithography techniques based on elastic stamping, contact printing, and polymer molding are being pursued for creating nanosized patterns on substrates, but none of these top-down fabrication methods is as fast, cheap, and flexible as photolithography (see Reference 8). As a result, many researchers are focusing on creating nanostructures from the bottom up.

The need for self-assembly. The success of bottom-up fabrication techniques is expected to depend to a great extent on exploiting the phenomenon of self-assembly—the tendency of atoms and molecules to naturally prefer certain structures or patterns.[10] Self-assembly is the basis for all biological synthesis and processing, from the formation of cell membranes to the organization of organic and inorganic components into structural composites such as shell or bone. These patterns of autonomous formation are specific to the materials themselves but can be changed by external influences such as temperature, pressure, and chemical reaction. Thus, carbon can be found in amorphous form (as in coal), as the hexagonal crystals of graphite (a dull, gray, relatively soft mineral), and as the octahedral, dodecahedral, and cubic crystals of diamond—transparent, brilliant, and the hardest substance known in nature.

Less than 20 years ago, scientists stumbled upon a fourth form of carbon—the *fullerene*, a synthetically produced, self-assembling, spherical molecular cage formed of hexagons and pentagons of linked carbon atoms. The ability to make fullerenes and carbon nanotubes (their cylindrical offshoots) has provided an amazingly useful building block material and encouraged researchers in the future of artificially controlled self-assembly. So far, most self-assembly experiments based on careful chemical and physical manipulation have produced nothing more complicated than layers of molecular films or size-specified crystals like the quantum dot. It is not yet clear how or if complex, designed patterns can be produced in this way.[11] The advent of pre-programmed self-assembly of complicated, interconnected nanoscale systems is still far off.

Quantum effects. Another difficulty arises from the unusual physical scale domain of nanoscience—right at the junction between the macroworld of Newtonian physics and the weird atomic world ruled by quantum mechanics. Researchers refer to this size domain as the *mesoscale*. While most nanostructures are likely to be built of hundreds of atoms or molecules, where Newtonian rules are dominant, they are not likely to be completely free from quantum effects.[12] Some of these effects may turn out to be quite helpful in opening opportunities at the mesoscale and smaller. The possibility of quantum computers is being investigated, for example—not a little box of interconnected nanoengineered circuit structures, but a beaker of liquid whose atomic particles are manipulated by nuclear magnetic resonance to control the “ones” and “zeros” of their nuclear spin.

The study of tunneling, exchange coupling, and other quantum phenomena may very well open up new possibilities and suggest innovative solutions to difficult problems. For example, the confluence of bandgap engineering, molecular-beam epitaxy, and nanofabrication capability recently made possible a new class of electronic devices based on quantum effects.[13,14] Still, being in the quantum realm—where the actual position of a particle is no more specific than a probability distribution—is disconcerting, and experiments have demonstrated that quantum mechanics can completely govern the behavior of small electrical devices (see Reference 12). Engineers are unlikely to be able to make reliable nanodevices until the physical principles that rule at the mesoscale are better understood.

5. Biotechnology

Since Watson and Crick first detailed the structure of DNA in 1952, scientists have come to understand how the simple, alternating pattern of chemicals in DNA encodes the great biological diversity encountered in the natural world. Progress by biologists, particularly in the past decade, has enabled many scientists to use this information to apply biological organisms, systems, and processes to industrial concerns, forming a new crosscutting technology platform known as *biotechnology*.

Biotechnology covers a myriad of processes and applications, from the fermentation of beer and wine to the use of recombinant DNA techniques to produce new drugs or specialized strains of commodity crops. In addition to the direct application and manipulation of biological elements to solve problems, biotechnology also includes a particularly rich subdiscipline known as *biomimesis*—the imitation of natural materials and process designs in the engineering of human-made structures and processes. Biomimetic materials, typically offering superior properties and functionality, hold tremendous potential for improving the capabilities of a wide range of industrial components and systems.

Broad Capabilities

Agricultural applications of biotechnology have been especially important, including the development of drought- and pest-resistant crop varieties and tremendous increases in crop yields. Further genetic optimization of food strains, along with the application of other farming best practices, have the potential to quadruple agricultural yields worldwide, significantly reducing world hunger.

Environmental biotechnology is a related specialty with enormous potential, offering novel, economical approaches to toxic cleanup and the treatment of industrial wastestreams. Bacteria have been used for many years to break down the organic components of sewage in municipal waste systems. Now genetically engineered microorganisms are being developed to “eat” such hazardous organic compounds as PCBs, ultimately leaving behind nothing more dangerous than water and CO_2. With continued genetic mapping work and studies of catabolic pathways, genetic engineering will allow the creation of “designer enviro-bugs” tailored to destroy specific toxic chemicals in situ at waste dumps or spill sites while leaving other components of the ecosystem untouched. Similar work has produced bugs capable of removing organic sulfur and other troublesome impurities from pulverized coal; if they can be made economical for routine coal cleaning, they will reduce the need for post-combustion cleanup of power plant emissions.

Meanwhile, industry is exploring the natural cleansing functions performed by wetland ecosystems—watery marshes whose minerals, vegetation, and bacteria can filter out or transform a variety of pollutants found in wastewater streams. Wetlands are already gaining in popularity as a means of treating municipal sewage, and electric utilities are working to engineer and optimize constructed wetlands for treating leachate from coal-combustion byproducts, coal-pile runoff, acid mine drainage, and other metal-bearing utility wastewater. To move wetland design from an art to a science, more research is needed on the physical, chemical, and biological mechanisms involved in the waste treatment, such as flocculation, decomposition, nutrient uptake, photosynthesis, and volatilization. Experimental investigation of practical issues—the best temperature, water volume, and choice of plant species—will allow cleanup processes to be optimized and matched to target pollutants. In addition, genetic engineering techniques can be applied to produce wetland plant and bacteria species with superior capabilities for trace element uptake, detoxification, and removal.

Bioengineering holds rich promise for improving industrial processes and materials as well. Pipe corrosion is estimated to be responsible for half of the forced outages in steam power plants, costing the U.S. power industry $5 to $10 billion a year. Biofilms—bacterial slimes that form on pipe interiors under some operating conditions—are partially responsible for the problem, with sulfate-reducing microbes attacking even some normally corrosion-resistant metals like stainless steel and aluminum. New bacterial strains are now being genetically engineered that not only can kill and replace the sulfate reducers but also consume oxygen that would otherwise oxidize and corrode the metal piping. Laboratory tests indicate that such protective biofilms could effect a 40-fold decrease in the corrosion rate of steel.

On the industrial materials side, biodegradable polyactides are being developed that may replace petroleum-based plastics in a range of industrial and commercial packaging applications, including injection-molded bottles, grocery bags, and foam food-service packaging. Widespread application of such new biodegradable substitutes would not only reduce the growing problem of landfill disposal of waste but also increase natural resource utilization and reduce the world's reliance on oil—all important sustainability targets.

Biofuels

Finding sustainable feedstock alternatives to petroleum fuel is a key R&D goal, with biologically produced gasoline substitutes topping the list. Analyses by the EPA show environmental benefits from using plant-derived ethanol in engines. Blending ethanol with gasoline, for example, increases the octane rating and fuel oxygen content, which facilitates more complete combustion and lower emissions of ozone and air toxics. Today, ethanol produced from corn through an acid digestion process is in limited use as gasoline blend stock, and the U.S. DOE is committed to tripling the use of bio-based fuels by 2010 under its Bioenergy 2020 program. Unfortunately, the economics of producing commodity ethanol from corn on a large scale are still cloudy. A switch from No. 2 yellow corn to sweet corn, which has a significantly higher ethanol yield per acre, is an option; however, sweet corn is more susceptible to rot and pest infestation, and the cost of improved drying, storage, and transportation schemes may offset the yield increase.

More radical cost reductions may come from two sources: finding a cheaper biological feedstock and developing a less expensive conversion process. In contrast to a starch or sugar such as corn as a source of ethanol, cellulose waste is plentiful and readily available as agricultural or forest residues and as municipal solid waste. Use of such waste could not only reduce feedstock costs and reserve agricultural land for food production, but also reduce the environmental insult of incineration or landfill expansion. Conversion of cellulosic materials to ethanol consists of two main steps: hydrolysis and fermentation. Hydrolysis can be accomplished either with acids or with cellulase enzymes. Although the two process routes are currently about equal in cost, acid hydrolysis—a mature technology—is expected to yield only small cost improvements. The cost of the enzymes themselves dominates the enzymatic processes. While it would be expensive to harvest enough natural enzyme to convert biomass to ethanol on a large scale, developing an inexpensive artificial enzyme or other chemical change catalyst through biomimetic research may provide a solution. (See Reference 15 for an excellent discussion of biotechnology for energy, including biofuels.)

The Promise of Biomimesis

Biomimetic materials are human-made substances that imitate either the result or the style of natural systems. Biomimetics is based on the idea that nature is the ultimate engineer—that, through evolution, nature has solved an optimization problem. Almost all biological materials are characterized by nanoscale internal structure and one or more of the following attributes:

- **Superior properties.** Biological materials often exhibit properties that exceed what is achievable with most human-made materials, often with starting substances that by themselves have unremarkable properties.
- **Hierarchical structures.** A composite, hierarchical architecture, one of the ways of achieving superior properties, is commonly found in biological systems; such structures are mostly inaccessible by conventional processing routes.
- **Superior assembly mechanisms.** Processes that can produce extremely small-scale features, often under surprisingly mild processing conditions (low temperature, low pressure, and benign chemical environments), are commonplace in biological systems.
- **Superior process control.** Processing methods that offer extraordinary control over the phase, directionality, size, or distribution of materials growth—the ultimate in tailored materials—are also typical of biological materials of construction.
- **Multifunctionality.** Biological materials often serve more than one function.
- **Adaptability.** Biological systems change in response to functional requirements over time scales ranging from rapid (deformation of leaves in the wind, which assume conical shapes to minimize aerodynamic drag) to the slowest pace of evolutionary change.

Mimicking natural material designs and processes is a young and tremendously fertile approach for developing new capabilities and achieving large improvements in existing systems. Traditionally, the search for new and improved materials has been guided by inspiration and prediction from physics and chemistry, and by serendipity. In recent years, however, there has been a growing awareness that biological designs or processing approaches applied to synthetic materials may offer significant improvements in performance over more traditional designs and fabrication methods. Moreover, biomimesis may very well be one of the few routes to the creation of tailored materials with “tunable” properties, which has long been a goal of materials science and engineering. With so-called advanced materials now representing about 20% of the total value of materials shipped in the United States, taking advantage of this opportunity will play an increasingly central role in technological and economic competitiveness.

Applications for biomimetic materials are as varied as their biological models—the shells of marine creatures, wood, bone, insect cuticle, eggshells, fibers, and natural adhesives, to name a few. Mollusk shells, with their extremely strong hierarchical physical structure, provide excellent models for fracture-resistant structural and high-temperature ceramics, thermal barrier coatings with superior resistance to thermal cycling, and even new concretes with high bend strength and damage tolerance. The high strength and extensibility of natural silk fibers provide inspiration for advanced, fiber-reinforced composites and superdurable filters. The keratin sheath on goat horns, which exhibit great notch insensitivity and damage tolerance, may show us how to manufacture superior surface layers for fracture-critical components.

There are numerous biological processing routes, both inside and outside of cells, that provide intriguing models for optimized manufacturing processes. They range from controlled deposition of the complex organic and mineral-phase composites that make up bones and shells, through self-assembly of oriented fibers and sheets, to spinning of fibers with high strengths directly from solution under ambient conditions. Only a start has been made at duplicating the precision, control, and intricate architectures of biological assembly mechanisms.

Biomimetic Applications

Mimicking natural processes synthetically can carry distinct practical advantages—the example of converting biomass to ethanol via biomimetic catalysis, as mentioned above, is a good example. Chemical reactions in natural systems are catalyzed by enzymes, which provide unparalleled efficiencies and specifications under near ambient conditions. Artificially produced enzymes may eventually match these high efficiencies and also accomplish reactions far more rapidly and under more aggressive process conditions. Because of the importance of catalytic processes in the chemical and manufacturing industries, research into the development of enzyme-based catalysts has potential for tremendous impact across a wide range of applications. Other high-payoff biomimetic opportunities—from industrial superglues to molecular electronics—are outlined next.

Proteinaceous adhesives. Marine animals such as mussels and barnacles produce protein-based adhesives that are both extremely strong and suited to wet environments. The mussel is capable of forming an adhesive bond under water in two to three minutes with a wide variety of natural and synthetic materials, including not only metals but also such slick surfaces as glass and Teflon. The ultimate tensile strength of this adhesive bond can be as high as 5 MN/m^2. In addition, these protein-based adhesives form bonds with metal surfaces that are more stable than the catechols now in industrial use for coating attachment. One obvious application in power generation is the bonding of corrosion-resistant coatings to piping and vessel interiors; however, the ability of proteinaceous adhesives to bond with such a large variety of materials opens their benefits to a wide range of manufacturing and processing applications that require wet environments.

Research into what gives mussel proteins their special properties has indicated that the amino-acids Dopa (a derivative of tyrosine) and lysine are most important.[16] Despite the volume of work that has been done, the complexity of this natural system and the difficulty of studying it experimentally have left a number of questions unanswered: how Dopa is produced from the tyrosine; how the stability of the Dopa-proteins is maintained during storage; how the Dopa-protein interacts with the enzyme catechol oxidase during secretion and setting; the precise nature of the bonding to filler molecules, such as collagen, chitin, and cellulose; and the nature of the cross-links formed.[17] It is also unclear whether the protein is extended or has some form of regular folded structure. Resolution of these issues will be central to the development of superior synthetic adhesives.

Artificial photosynthesis for photovoltaic cells. Plant photosynthesis has much in common with photovoltaic (PV) electricity production: both require the harvesting of photons from sunlight, formation and separation of positive and negative charges, and transport of these charges. While plants then use the charges to electrochemically synthesize hydrocarbons for food, PV cells consolidate individual charges in a circuit to produce DC current. Biomimetic approaches to light gathering and charge separation have shown tantalizing promise for advancing the efficiency and economy of PV cells.

Photosynthesis research has led to the development of a “sensitizer-antenna molecular device” for photoelectrochemical light gathering, and the device has been incorporated into prototype solar cells assembled from a trimeric ruthenium complex adsorbed on films of nanometer-sized particles of titanium dioxide.[18] The prototype performance has been very attractive. Conversion efficiencies of 7.1% have been logged under full sunlight, and efficiency rises to 12% under diffuse daylight—better than the cell performance of conventional silicon devices under low-light conditions.[19,20] The performance of this prototype has been confirmed, and new cell combinations are being examined for further improvement. Research progress in this area is expected to be rapid.[21,22]

On the charge separation front, researchers are investigating the use of structures consisting of metal phosphonates and organic molecules, such as porphyrins and viologens that respond to light by producing electron-hole pairs.[23] This approach is particularly exciting because the structures exhibit the capability of self-assembly[24]; combining self-assembly under “mild” conditions with the biomimetic antenna systems described above is likely to substantially reduce the costs of cell manufacture. Before working cells can become a reality, however, several practical problems—including the crucial step of electron collection—must be solved.

Photo-induced decomposition of water. Effective processes for splitting water into molecular hydrogen and oxygen are of special interest for hydrogen use as a non-carbonaceous fuel, either in direct combustion or as the primary consumable in fuel cells. It has been known for many years that zinc sulfide particles in aqueous suspension catalyze the photodecomposition of water. Over several decades of study, however, hydrogen yields for this approach remained low, and anodic corrosion of the catalysts by oxygen proved problematic. More recently, interest has shifted to a biochemical approach, combining biological photosystems—chloroplasts—with artificial substrates. Spinach chloroplasts immobilized with the enzyme hydrogenase and polyethylene particles coated with chlorophyll extracted from algae have been explored. Yields, however, are still low.

Recent experiments with wild and mutant algae in the chlamydomonas family suggest that the maximum thermodynamic conversion efficiency for converting light energy into chemical energy can potentially be doubled from about 10% to 20% when the potential difference between water oxidation (oxygen evolution) and proton reduction (hydrogen evolution) can be spanned by a single photon instead of the conventional two.[25] Further investigation of this approach, especially to discover a biomimetic model for the synthesis process, may result in substantial improvements.

If a technique can indeed be developed for splitting water at industrially significant rates, novel process cycles may improve overall economics and provide additional benefits. For example, desalination of seawater—currently accomplished by high-temperature evaporation and condensation or by high-pressure reverse osmosis—could be integrated into the photo-induced decomposition process.[26] The hydrogen split out of seawater could be combusted in a boiler or fed into a fuel cell to produce electricity. The water vapor resulting from combustion (or electrochemical reaction) could then be condensed and purified by conventional water-treatment technology to provide potable water. Such a cycle would, of course need to be economically competitive with the conventional desalination approaches.

Proton pumping for low-temperature fuel cells. Fuel cells appear to be a power generation technology tailor-made for a sustainable future. Producing electricity electrochemically rather than through fuel combustion, they have no moving parts and generate no noise or pollutant emissions. Still, the fuel cells now under development must operate at medium to high temperatures—some as high as 900ºC. An ambient-temperature fuel cell would represent an important advance of technology. Biomimetic research into ion transport in plants at the macromolecular level may make such a device possible.

The electricity generation function of current fuel cells depends on catalytically stripping a hydrogen ion—a proton—from a hydrogen atom and inducing it to travel from the cell's anode, through an electrolyte, to its oxygen-bathed cathode. Electricity is generated when the electron remaining from each proton-stripped atom travels from the anode through an external circuit to reunite at the cathode. The process creates water and heat in addition to electricity.

The ability of some biological systems to transport ions across cellular and intracellular membranes provides a model for a lower-temperature, proton-pumping process. Specifically, bacteriorhodopsin (bR), a pigment in bacteria that grow in salt marshes, is a light-driven proton pump.[27] In other words, bR uses the energy derived from light to pump protons across a membrane. It is postulated that a biomimetic (bR-like), proton-transmitting membrane could be the basis of an ambient-temperature fuel cell. Recent research has aimed mainly at characterizing the structure and function of bR, but the emphasis is already shifting to investigation of how this phenomenon could be applied in a man-made system.[28]

Despite substantial progress, the process of proton pumping is not yet fully understood on a molecular level, and a more complete understanding of the photochemistry is required. Still, if biomimetic proton pumping could be applied to developing a low-temperature fuel cell, it would carry with it real advantages in cost, weight, cycle life, and construction materials.

6. Electronics and Semiconductors

Electronics and semiconductors are treated in parallel in this report because the energy issues in these sectors are very similar. Electronics and semiconductors are widely credited as being one of the principal engines of economic growth and productivity in the developed world. In fact, the growth in worker productivity experienced in the United States between 1995 and 2000 is thought to be the result of a spurt in the application of semiconductors to new functions not previously imagined. The growing contribution of digital technologies—those that rely on the products of the chip industry—to economic growth and prosperity has increased the strategic focus of semiconductor executives to the importance of a reliable electricity supply.

The energy implications for the electronics and semiconductors differ strongly from the situation in primary metal production. Although power quality and reliability are important in both industries, the impact of power-quality problems, especially those of short duration, are larger for the semiconductor sector in terms of lost production and equipment damage. Moreover, the semiconductor fabrication process is sensitive to power-quality events of very short duration (minutes to seconds to milliseconds), whereas aluminum smelters can recover from an outage lasting several hours as long as the electrolyte does not freeze.

Semiconductor sales have been increasing steadily, almost since the beginning of the industry. As **Figure III-29** shows, sales increased from about $1 billion in the late 1960s to the all time peak of $204 billion in 2000. After this point, sales declined to about $140 billion in 2002. However, an upturn in sales is evident for 2003, the last year for which data are available.

It is notable that semiconductor sales have increased exponentially over nearly four decades, indicating the strong growth in this sector, and also the continuing diversity in semiconductor applications that creates multiple markets for ship suppliers (**Figure III-30**). Even as the market for some applications such as standalone PCs becomes saturated, new applications emerge to maintain market growth. Currently, for example, much of the recent growth in semiconductor sales reflects the demand for chips destined for service in small hand-held devices, such as cell phones and pocket PCs.

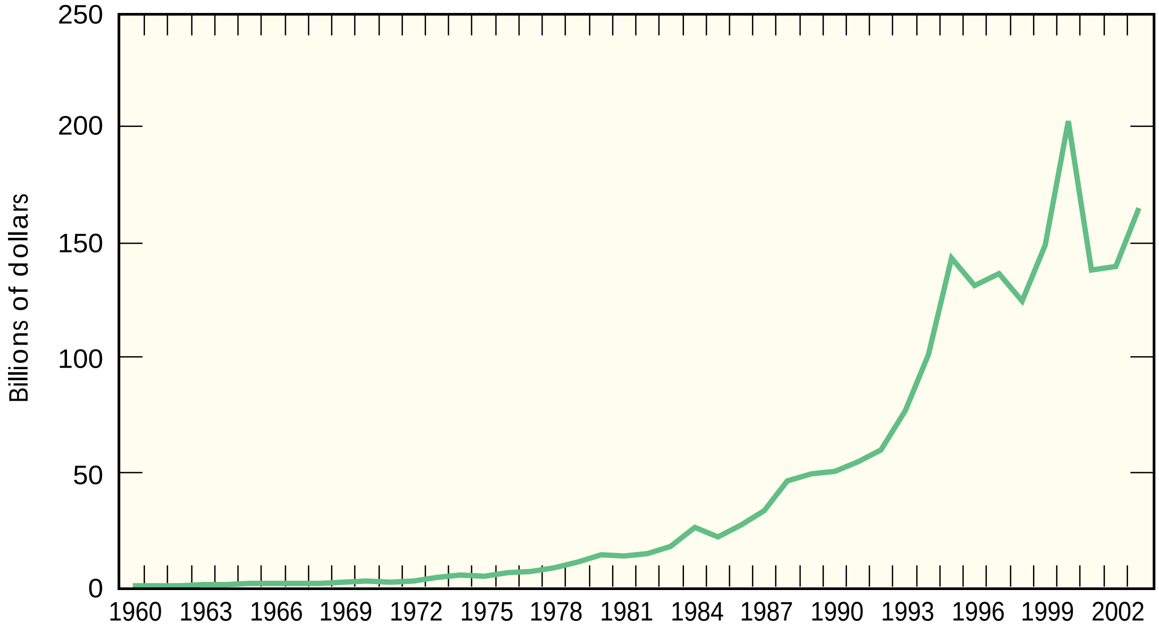


Figure III-29. Global semiconductor shipments.

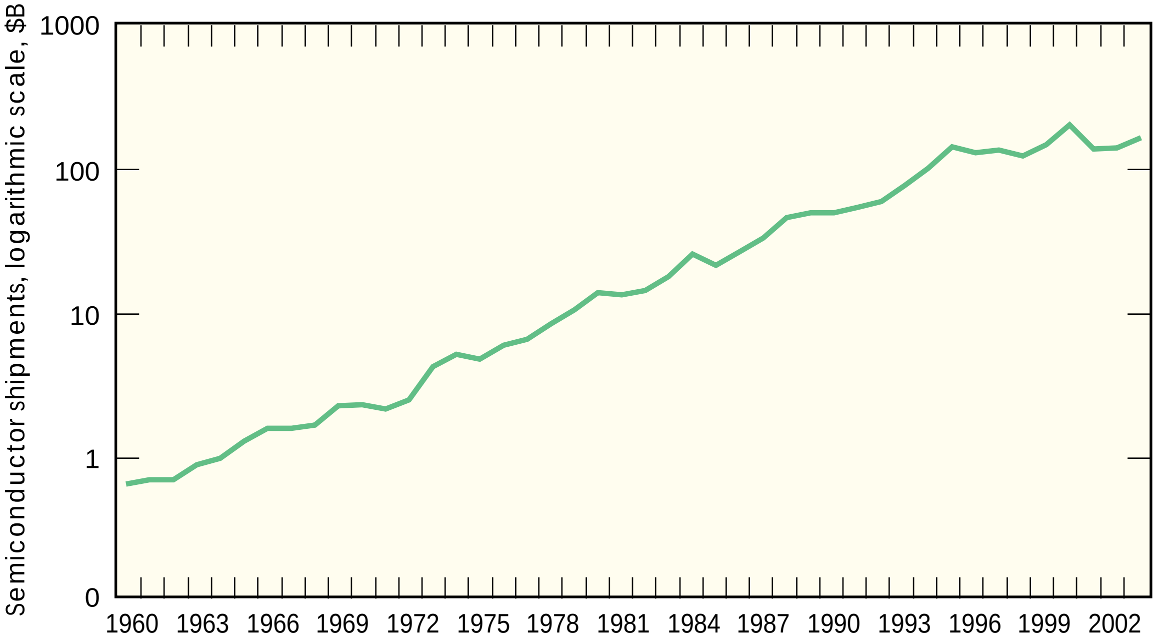


Figure III-30. Semiconductor sales have followed an exponential growth law since the 1960s.

Regional semiconductor sales follow the same pattern as overall global sales (**Figure III-31**). Note, however, that the rebound in sales in 2003 is most pronounced in the Asia–Pacific region and in Japan.

RD&D: Goals and Challenges

Key goals for the electronics and semiconductor industry are to—

- Improve building performance through lighting upgrades and HVAC improvements
- Reduce energy requirements and costs by improving process efficiency
- Reduce power drain and leakage from processor chips to reduce heat loads and prolong battery life
- Add monitoring systems to ensure that critical equipment is operating under optimal conditions
- Reduce peak load requirements
- Improve reliability and power quality by adding on-site generation and storage systems and other distributed energy resources.

One area in which substantial improvements appear possible is that of Internet data centers. These facilities, the “brains” of the Internet, are responsible for the transmission and delivery of billions of messages daily. Anecdotal evidence indicates that the power systems comprise as much as two-thirds of the total cost of large Internet data centers. Recent

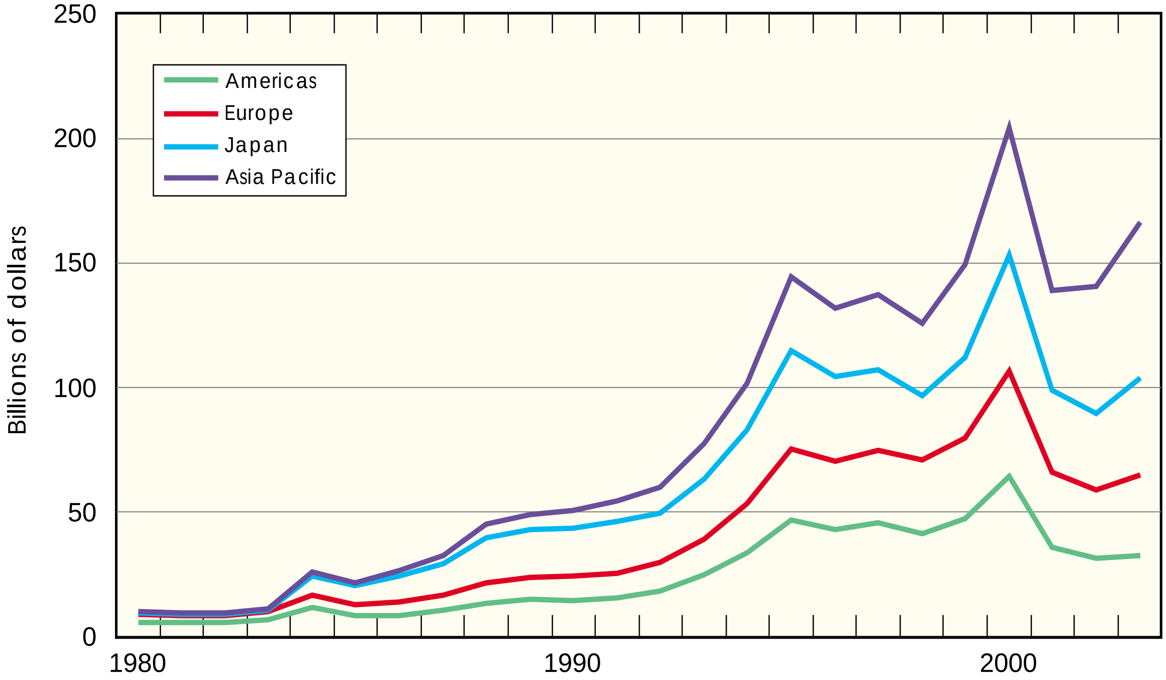


Figure III-31. Regional chip sales parallel overall global sales.

studies have suggested specific opportunities to reduce the energy requirements of Internet data centers. These opportunities include the development of more energy-efficient processor chips to reduce the heat load in the buildings, high-efficiency power supplies that maintain efficiency over a wide range of loads, and high-efficiency fluid cooling systems that use heat pipes to isolate the fluid from the electronic components.

These solutions are important, but by themselves, they do not appear to provide the integrated solutions needed by all areas of high-tech manufacturing. These industries, including electronics and semiconductors, need a truly smart delivery system. The attributes of a smart delivery system of the future are described below in the discussion of service industries.

7. Industrial Automation

Information and control technology is of longstanding importance for processes in the iron, steel, and pulp and paper industries. This is true for all the steps in the chain—from sensors for a wide variety of parameters to signal processing, modeling, simulation, and adaptive control. The development of modern information technology both drives and is driven by the productivity in different types of industry.

The trends in industrial information technology-based process controls are moving toward increased integration between the production process, the collected resources of the company, and the customers' needs. In global business groups, control can be centralized and extended to geographically dispersed production units. For the energy-intensive industries, the development of information technology can further strengthen these ongoing trends. Examples are the localization of production closer to increasing markets, the advent of new materials substituting for old ones, new raw materials and recycling, and smaller production units adapted to market needs and local conditions but which can be controlled globally.

Industrial automation is developing toward many objectives. The intelligence in the control systems comes closer to the process but also closer to the customer. From having been a pure process control, where material and energy consumption and environmental impact was optimized, it is now moving also toward the handling of ”soft” parameters such as quality and delivery times.

8. Measurement and Control Technology

Measurement and control technology affects and will continue to span all end-use technologies; it is therefore vital to ensuring that energy is optimally utilized in the end-use sector. In this case, careful measurements are translated in real time into commands that control the conversion of energy into useful work. Examples are the measurement and then optimization of automobile emissions, such as CO, NO_x, and hydrocarbons, to optimize combustion, and the measurement of physical and chemical parameters such as pressure, viscosity, flow, and chemical species concentration for industrial control processes.

Advanced sensors are key to accurate measurements. These sensors not only have to accurately monitor the necessary parameter(s), but also must often work in harsh environments, such as high temperatures, caustic fluids, and highly abrasive flows. They must also be economical, so that the benefit of its use outweighs the cost of the sensor.

Goals include the development or use of materials that can withstand harsh environments, packaging that allows operation in destructive environments, pattern recognition, artificial intelligence, and fuzzy logic technologies for real-time signal processing and data analyses, and wireless two-way communication, all using inexpensive materials and manufacturing processes.

9. Modeling and Simulations

Modeling and simulation technologies are critical to the development of any successful technology, including end-use technologies of energy. Models can help understand the effect of new technologies on economies and the environment, evaluate the effect of new technologies on the policy goals of governments, and assist in optimizing the design of technologies and their placement in the infrastructure. In addition, models can assess risk–benefit ratios associated with the introduction of new technologies (e.g., hydrogen fuel). As computational capabilities advance, more and more realistic simulations can be achieved. Software keeps pace with, and some would say even helps drive, computational speed and memory capacity.

Goals include high-resolution simulations of manufacturing operations, power generation, transmission and storage operations, emissions from internal combustion engines, lifecycle costs, and the environmental effects of alternative systems such as fuel cells, and the optimization of building envelopes in terms of economics, efficiency, and environmental impacts, and simulations of flows around vehicles, especially trucks.

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IV. RD&D Investments

A limited study such as this cannot estimate in detail the RD&D investments needed to develop the technologies discussed here to the point where they are ready for evaluation by the marketplace. Effort expended jointly by governments and industry on such studies will be fruitful, not only in identifying targets and identifying methods to encourage capital investments, but also in highlighting the global scope that effective efforts demand.

An effort was begun concerning capital investment costs for supply technologies in the first phase of this study. In 1999, the U.S. PCAST[1] study identified the need for an international Strategic Energy Cooperation Fund to supplement existing budgets and recommended a U.S. government contribution of $500 million per year by 2005. Of this sum, $100 million was identified for end-use technologies, plus another $240 million for government-industry partnerships, industrial research and demonstration cooperation, and deployment, all primarily in end-use technologies. The total U.S. government energy R&D (not demonstration) budget is currently around $2 billion per year, of which about one-third, or $660 million, is spent on end-use technologies. Adding this to the supplement suggested by PCAST yields $1 billion per year on all R&D. If we take the U.S. economy as approximately 25% of the global economy, a global expenditure on international cooperation on energy end-use technologies of four times this amount, or $4 billion per year, seems warranted. (For comparison and to put this number in perspective, the IEA has estimated the global capital investment needed in the energy infrastructure is $16 trillion in the period to 2030.[2] Thus, $4 billion per year for R&D seems more than justified at the front end, and is in fact very conservative).

These conservative figures do not include monies for significant demonstration activities. The development portion can be much more expensive, as illustrated by the expense associated with the demonstration of known technologies. Solar photovoltaics, ethanol, wind, and gas turbines have all been studied in detail and require or will require about $2 billion each to bring to market, most of that in demonstration. The technologies identified in this report number about 50 and would thus require a collective investment of about $100 billion over their lifespan of 20–40 years for just the most important end-use technologies. Some will cost more and others less, and still others will arrive on the scene. In addition, more detailed analyses, along the lines of those done to date for a more limited scope, would be useful.[3]

Absent these efforts at R&D and then demonstration, technologies for energy end-use will not be ready for the marketplace in the timeframes required by even pessimistic scenarios of world economic development. In addition, end-use technologies will have as much impact as anything on overall energy use and to the goals of *Accessibility*, *Availability*, and *Acceptability* of energy and energy services.

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Annex A: Study Group Members and Invited Experts

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* The Invited Experts made useful contributions but did not participate in the study.

Annex B: Abbreviations, Acronyms, and Definitions

Factor	Name	Symbol
10^{18}	exa	E
10^{15}	peta	P
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{-9}	nano	n

Accessibility	Convenience, cost, and efficiency of energy and energy services
Availability	Quality and reliability of energy and energy services
Acceptability	Environmental acceptability of energy and energy services
ACV	Advanced conventional vehicle
AEV	All-electric vehicle
AHSS	Advanced high-strength steel
BPA	Bonneville Power Administration
BTU	British thermal unit ($\cong 24 \times 10^9$ toe)
CEFIC	European Chemical Industry Council
C	Carbon
CHP	Combined heat and power
CIS	Commonwealth of Independent States, or the former Soviet Union
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
DG	Distributed generation
DMFC	Direct-methanol fuel cell
EMF	Electromagnetic field
End-use technology	Conversion to useful work, as in process heat, lighting, or transportation
EPRI	Electric Power Research Institute, Palo Alto, California, United States
ETOH	Ethanol
FACTS	Flexible AC transmission system
FAME	Fatty acid methyl ester
GEP	Global Energy Perspectives, by N. Nakicenovic, A. Grübler, and A. McDonald, International Institute for Applied Systems Analysis and World Energy Council, Cambridge University Press, 1998

GDP	Gross domestic product
GWP	Global world product
HC	Hydrocarbons, usually unburned
HEV	Hybrid electric vehicle
HHV	High heating value
HSR	High-speed rail
HTS	High-temperature superconducting
HVAC	high-voltage alternating current
HVDC	high-voltage direct current
I&CT	information and communication technologies
IPHE	International Partnership for the Hydrogen Economy
ICE	Internal combustion engine
Joules	10^{18} Joules (~10^{15} BTU)
KAM	Ecocyclic Pulp Mill (Sweden)
kWh	kilowatt-hour
LHV	low heating value
LPG	Liquefied petroleum gas
maglev	magnetic levitation
MHD	Magnetohydrodynamic
Micro-CHP	micro-combined heat and power
NAFTA	North American Free Trade Agreement
NO_x	Various nitrogen oxides, primarily NO and NO_2
OECD	Organization for Economic Co-operation and Development
PEM	Proton exchange membrane
PV	Photovoltaic
RD&D	research, development, and demonstration
SMES	superconducting magnetic-energy storage
SOFC	solid-oxide fuel cell
SST	supersonic transport
T&D	transmission and distribution
TGV	Train á Grande Vitesse
TMP	thermomechanical production of pulp
toe	tonne of oil (energy) equivalent
UNEP	United Nations Environmental Programme
WAMS	Wide-area measurement system
WEC	World Energy Council

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Energy End-Use Technologies for the 21st Century
ISBN 0 946121 15 X