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Global Energy System

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Global energy consumption in the last half century has increased very rapidly and is expected to continue to grow over the next 50 years. However, we expect to see significant differences between the last 50 years and the next. The past increase was stimulated by relatively "cheap" fossil fuels and increased rates of industrialization in North America, Europe, and Japan; yet while energy consumption in these countries continues to increase, additional factors are making the picture for the next 50 years more complex. These additional complicating factors include the very rapid increase in energy use in China and India (countries representing about a third of the world's population); the expected depletion of oil resources in the not-too-distant future; and the effect of human activities on global climate change. On the positive side, the renewable energy (RE) technologies of wind, biofuels, solar thermal, and photovoltaics (PV) are finally showing maturity and the ultimate promise of cost competitiveness.

Statistics from the International Energy Agency (IEA) World Energy Outlook 2004 show that the total primary energy demand in the world increased from 5536 GTOE in 1971 to 10,345 GTOE in 2002, representing an average annual increase of 2% (see Table 1.1 and Figure 1.1).[1]

Of the total primary energy demand in 2002, fossil fuels accounted for about 80%, with oil, coal, and natural gas accounting for 35.5, 23, and 21.2%, respectively. Biomass accounted for 11% of all the primary energy in the world, with almost all of it being traditional biomass for cooking and heating in developing countries; biomass is used very inefficiently in these applications.

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[1] The energy data for this chapter came from many sources, which use different units of energy, making it difficult to compare the numbers. The conversion factors are given here for a quick reference: MTOE = Mega tons of oil equivalent; 1 MTOE = 4.1868×10^4 TJ (Terra Joules) = 3.968×10^{13} Btu., GTOE = Giga tons of oil equivalent; 1 GTOE = 1000 MTOE; Quadrillion Btu, also known as Quad: 10^{15} British Thermal Units or Btu; 1 Btu = 1055 J, 1 TWh = 10^9 kWh, 1 kWh = 3.6×10^6 J.

TABLE 1.1 World Total Energy Demand (MTOE)

Energy Source/Type	1971	2002	Annual Percentage of Change 1971–2002
Coal	1407	2389	1.7
Oil	2413	3676	1.4
Gas	892	2190	2.9
Nuclear	29	892	11.6
Hydro	104	224	2.5
Biomass and Waste	687	1119	1.6
Other Renewables	4	55	8.8
Total	5536	10,345	2.0

Source: From IEA, *World Energy Outlook*, International Energy Agency, Paris, 2004. With permission.

The last 10 years of data for energy consumption from British Petroleum Corp. (BP) also shows that the average increase per year was 2%. However, it is important to note (from Table 1.2) that the average worldwide growth from 2001 to 2004 was 3.7% with the increase from 2003 to 2004 being 4.3%. The rate of growth is rising mainly due to the very rapid growth in Pacific Asia, which recorded an average increase from 2001 to 2004 of 8.6%.

More specifically, China increased its primary energy consumption by 15% from 2003 to 2004. Unconfirmed data show similar increases continuing in China, followed by increases in India. Fueled by high increases in China and India, worldwide energy consumption may continue to increase at rates between 3 and 5% for at least a few more years. However, such high rates of increase cannot continue for long. Various sources estimate that the worldwide average annual increase in energy consumption will be 1.6%–2.5% (IEA 2004; IAEA 2005). Based on a 2% increase per year (average of the estimates from other sources), the primary energy demand of 10,345 GTOE in 2002 would double by 2037 and triple by 2057. With such high energy demand expected 50 years from now, it is important to look at all of the available strategies to fulfill the future demand, especially for electricity and transportation.

Although not a technical issue in the conventional sense, no matter what types of engineering scenarios are proposed to meet the rising energy demands world population, as long as exponential growth in world population continues, the attendant problems of energy and food consumption, as well as environmental degradation, may have no long-term solution (Bartlett 2004). Under current demographic trends, the United Nations forecasts a rise in the global population to around 9 billion in the year 2050. This increase in 2.5 billion people will occur mostly in developing countries with aspirations for a higher standard of living. Thus, population growth should be considered as a part of the overall supply and demand picture to assure the success of future global energy and pollution strategy.

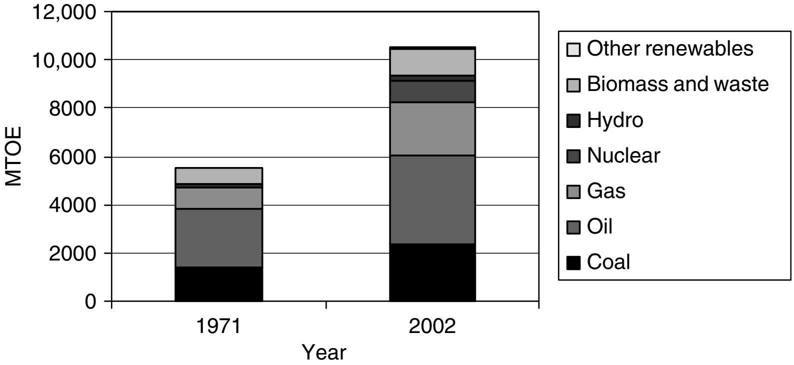


FIGURE 1.1 **(See color insert following page 774.)** World primary energy demand (MTOE). (Data from IEA, *World Energy Outlook*, International Energy Agency, IEA, Paris, 2004. With permission.)

TABLE 1.2 Primary Energy Consumption (MTOE)

Region	2001	2002	2003	2004	Average Increase/Year (%)	2004 Change Over 2003 (%)
North America including U.S.A.	2681.5	2721.1	2741.3	2784.4	1.3	1.6
U.S.A.	2256.3	2289.1	2298.7	2331.6	1.1	1.4
South and Central America	452.0	454.4	460.2	483.1	2.2	5.0
Europe and Euro–Asia	2855.5	2851.5	2908.0	2964.0	1.3	1.9
Middle East	413.2	438.7	454.2	481.9	5.3	6.1
Africa	280.0	287.2	300.1	312.1	3.7	4.0
Asia Pacific	2497.0	2734.9	2937.0	3198.8	8.6	8.9
World	9179.3	9487.9	9800.8	10,224.4	3.7	4.3

This data does not include traditional biomass, which was 2229 MTOE in 2002 according to IEA data.
Source: From British Petroleum Corporation, *BP Statistical Review of World Energy, 2006*, British Petroleum, London, 2006, http://www.bp.com/statisticalreview/.

1.1 Major Sectors of Primary Energy Use

The major sectors using primary energy sources include electrical power, transportation, heating, industrial, and others, such as cooking. The IEA data shows that the electricity demand almost tripled from 1971 to 2002. This is not unexpected because electricity is a very convenient form of energy to transport and use. Although primary energy use in all sectors has increased, their relative shares except for transportation and electricity have decreased (Figure 1.2). Figure 1.2 shows that the relative share of primary energy for electricity production in the world increased from about 20% in 1971 to about 30% in 2002. This is because electricity is becoming the preferred form of energy for all applications.

Figure 1.3 shows that coal is presently the largest source of electricity in the world. Consequently, the power sector accounted for 40% of all CO_2 emissions in 2002. Emissions could be reduced by increased

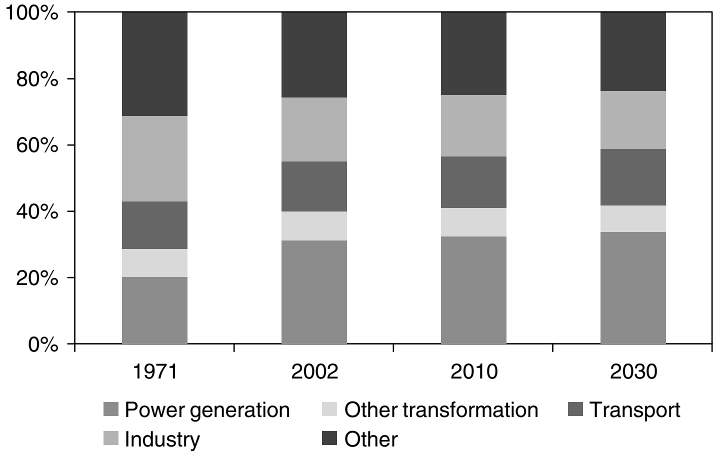


FIGURE 1.2 **(See color insert following page 774.)** Sectoral shares in world primary energy demand. (Data and forecast from IEA, *World Energy Outlook*, IEA, Paris, 2004. With permission.)

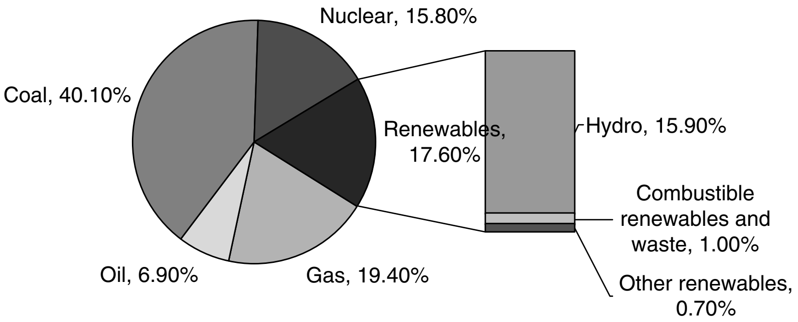
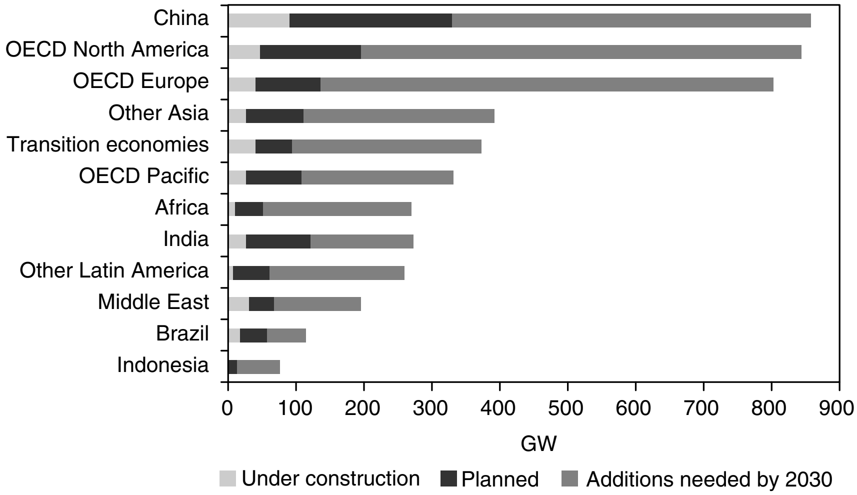


FIGURE 1.3 World electricity production by fuel in 2003. (Data from IEA, *Renewables Information*, IEA, Paris, 2005. With permission.)

use of RE sources. All RE sources combined accounted for only 17.6% share of electricity production in the world, with hydroelectric power providing almost 90% of it. All other RE sources provided only 1.7% of electricity in the world. However, the RE technologies of wind power and solar energy have vastly improved in the last two decades and are becoming more cost effective. As these technologies mature and become even more cost competitive in the future they may be in a position to replace a major fraction of fossil fuels for electricity generation. Therefore, substituting fossil fuels with RE for electricity generation must be an important part of any strategy of reducing CO_2 emissions into the atmosphere and combating global climate change.

1.2 Electrical Capacity Additions to 2030

Figure 1.4 shows the additional electrical capacity forecast by IEA for different regions in the world. The overall increase in the electrical capacity is in general agreement with the estimates from IAEA (2005)



Source: IEA analysis. Data for plants under construction and planning are from plants (2003).

FIGURE 1.4 Electrical capacity requirements by region. (From IEA, *World Energy Outlook*, IEA, Paris, 2004. With permission.)

which project an average annual growth of about 2%–2.5% up to 2030. It is clear that of all countries, China will add the largest capacity with its projected electrical needs accounting for about 30% of the world energy forecast. China and India combined will add about 40% of all the new capacity of the rest of the world. Therefore, what happens in these two countries will have important consequences on the worldwide energy and environmental situation. If coal provides as much as 70% of China's electricity in 2030, as forecasted by IEA (IEA 2004), it will certainly increase worldwide CO_2 emissions, and further increase global warming.

1.3 Transportation

Transportation is another sector that has increased its relative share of primary energy. This sector has serious concerns as it is a significant source of CO_2 emissions and other airborne pollutants, and it is almost totally based on oil as its energy source (Figure 1.5; Kreith, West, and Isler 2002). In 2002, the transportation sector accounted for 21% of all CO_2 emissions worldwide. An important aspect of future changes in transportation depends on what happens to the available oil resources, production and prices. At present, 95% of all energy for transportation comes from oil.

As explained later in this chapter, irrespective of the actual amount of oil remaining in the ground, oil production will peak soon. Therefore, the need for careful planning for an orderly transition away from oil as the primary transportation fuel is urgent. An obvious replacement for oil would be biofuels such as ethanol, methanol, biodiesel, and biogases. Some believe that hydrogen is another alternative, because if it could be produced economically from RE sources or nuclear energy, it could provide a clean transportation alternative for the future. Some have claimed hydrogen to be a "wonder fuel" and have proposed a "hydrogen-based economy" to replace the present carbon-based economy (Veziroglu and Barbir 1992). However, others (Shinnar 2003; Kreith and West 2004; Mazza and Hammerschlag 2005) dispute this claim based on the lack of infrastructure, problems with storage and safety, and the lower efficiency of hydrogen vehicles as compared to plug-in hybrid or fully electric vehicles (West and Kreith 2006). Already hybrid-electric automobiles are becoming popular around the world as petroleum becomes more expensive.

The environmental benefits of renewable biofuels could be increased by using plug-in hybrid electric vehicles (PHEVs). These cars and trucks combine internal combustion engines with electric motors to

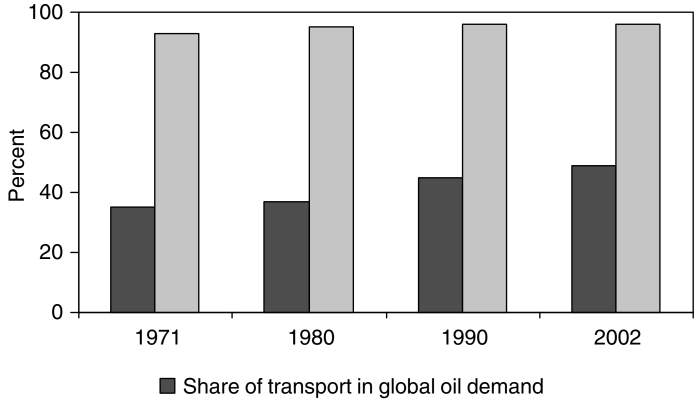


FIGURE 1.5 Share of transport in global oil demand and share of oil in transport energy demand. (Data and forecast from IEA, *World Energy Outlook*, IEA, Paris, 2004. With permission.)

maximize fuel efficiency. PHEVs have more battery capacity that can be recharged by plugging it into a regular electric outlet. Then these vehicles can run on electricity alone for relatively short trips. The electric-only trip length is denoted by a number, e.g., PHEV 20 can run on battery charge for 20 miles. When the battery charge is used up, the engine begins to power the vehicle. The hybrid combination reduces gasoline consumption appreciably. Whereas the conventional vehicle fleet has a fuel economy of about 22 mpg, hybrids such as the Toyota Prius can attain about 50 mpg. PHEV 20s have been shown to attain as much as 100 mpg. Gasoline use can be decreased even further if the combustion engine runs on biofuel blends, such as E85, a mixture of 15% gasoline and 85% ethanol (Kreith 2006; West and Kreith 2006).

Plug-in hybrid electric technology is already available and could be realized immediately without further R&D. Furthermore, a large portion of the electric generation infrastructure, particularly in developed countries, is needed only at the time of peak demand (60% in the United States), and the rest is available at other times. Hence, if batteries of PHEVs were charged during off-peak hours, no new generation capacity would be required. Moreover, this approach would levelize the electric load and reduce the average cost of electricity, according to a study by the Electric Power Research Institute (EPRI) (Sanna 2005).

Given the potential of PHEVs, EPRI (EPRI 2004) conducted a large-scale analysis of the cost, battery requirements, economic competitiveness of plug-in vehicles today and in the future. As shown by West and Kreith, the net present value of lifecycle costs over 10 years for PHEVs with a 20-mile electric-only range (PHEV20) is less than that of a similar conventional vehicle (West and Kreith 2006). Furthermore, currently available nickel metal hydride (NiMH) batteries are already able to meet required cost and performance specifications. More advanced batteries, such as lithium-ion (Li-ion) batteries, may improve the economics of PHEVs even further in the future.

1.4 World Energy Resources

With a view to meet the future demand of primary energy in 2050 and beyond, it is important to understand the available reserves of conventional energy resources including fossil fuels and uranium, and the limitations posed on them due to environmental considerations.

1.4.1 Conventional Oil

There is a considerable debate and disagreement on the estimates of "ultimate recoverable oil reserves." However, there seems to be a good agreement on the amount of "proven oil reserves" in the world. According to British Petroleum (2006), total identified or proven world oil reserves at the end of 2005 were 1200.7 billion barrels. This estimate is close to the reserves of 1266 billion barrels from other sources listed by IEA (IEA 2004). The differences among them lie in their accounting for the Canadian tar sands. Considering the present production rate of over 80 million barrels per day, these reserves will last for about 41 years if there is no increase in production. Of course, there may be additional reserves that may be discovered in the future. A recent analysis by the U.S. Energy Information Agency (2006) estimates the ultimately recoverable world oil reserves (including resources not yet discovered) at between 2.2×10^{12} barrels (bbl) and 3.9×10^{12} bbl with a mean estimate of the USGS at 3×10^{12} bbl.

Ever since petroleum geologist M. King Hubbert correctly predicted in 1956 that U.S. oil production would reach a peak in 1973 and then decline (Hubbert 1974), scientists and engineers have known that worldwide oil production would follow a similar trend. Today, the only question is when the world peak will occur. Bartlett (2002) has developed a predictive model based on a Gaussian curve similar in shape to the data used by Hubbert as shown in Figure 1.6. The predictive peak in world oil production depends on the assumed total amount of recoverable reserves.

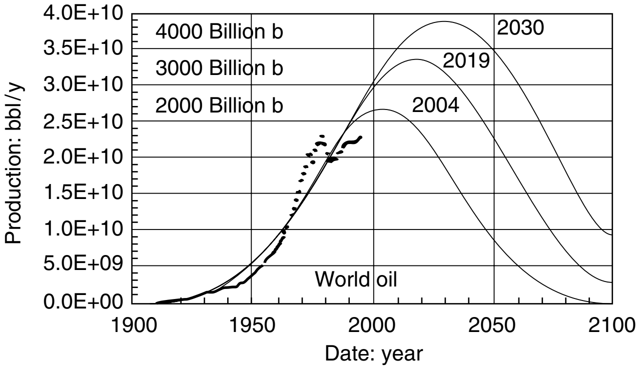


FIGURE 1.6 World oil production vs. time for various amounts of ultimate recoverable resource. (From Bartlett, A. A., *Mathematical Geology*, 32, 2002. With permission.)

If BP's estimations of oil reserves are correct, we may have already peaked in world oil production. If, however, estimates of the ultimate reserves (discovered and undiscovered) are used, we may expect the oil production to increase a little longer before it peaks. However, changing the total available reserves from 3×10^{12} bbl to 4×10^{12} bbl increases the predicted time of peak production by merely 11 years, from 2019 to 2030. There is no question that after the world peak is reached and oil production begins to drop, either alternative fuels will have to be supplied to make up the difference between demand and supply, or the cost of fuel will increase precipitously and create an unprecedented social and economic crisis for our entire transportation system.

The present trend of yearly increases in oil consumption, especially in China and India, shortens the window of opportunity for a managed transition to alternative fuels even further. Hence, irrespective of the actual amount of oil remaining in the ground, peak production will occur soon. Therefore, the need for starting to supplement oil as the primary transportation fuel is urgent because an orderly transition to develop petroleum substitutes will take time and careful planning.

1.4.2 Natural Gas

According to BP (2006), the total proven world natural gas reserves at the end of 2004 were 179.5 trillion m^3. Considering the production rate of gas in 2004, with no increase in production thereafter, these reserves would last for 67 years. However, production of natural gas has been rising at an average rate of 2.5% over the past four years. If production continues to rise because of additional use of CNG for transportation and increased power production from natural gas, the reserves would last for fewer years. Of course, there could be additional new discoveries. However, even with additional discoveries, it is reasonable to expect that all the available natural gas resources may last from about 50 to 80 years, with a peak in production occurring much earlier.

1.4.3 Coal

Coal is the largest fossil resource available to us and the most problematic from an environmental standpoint. From all indications, coal use will continue to grow for power production around the world because of expected increases in China, India, Australia, and other countries. From an environmental point of view, this would be unsustainable unless advanced "clean coal technology" (CCT) with carbon sequestration is deployed.

Clean coal technology is based on an integrated gasification combined-cycle (IGCC) that converts coal to a gas that is used in a turbine to provide electricity with CO_2 and pollutant removal before the fuel is burned (Hawkins, Lashof, and Williams 2006). According to R.C. Kelly, President and Chief Executive Officer of Minneapolis-based Xcel Energy, the company is about to build such a plant in Colorado, U.S.A. The plant will capture CO_2 and inject it underground, possibly in depleted oil fields. According to Kelly, an IGCC plant can cost 20% more to build than a conventional coal plant, but is more efficient to operate (Associated Press 2006). According to an Australian study (Sadler 2004), no carbon capture and storage system is yet operating on a commercial scale, but may become an attractive technology to achieve atmospheric CO_2 stabilization.

According to BP, the proven recoverable world coal resources were estimated to be 909 billion tons at the end of 2004 with a reserve to production ratio (R/P) of 164 years. The BP data also shows that coal use increased at an average rate of 6% from 2002 to 2005, the largest increase of all fossil resources. Because China and India are continuing to build new coal power plants, it is reasonable to assume that coal use will continue to increase for at least some years in the future. Therefore, the R/P ratio will decrease from the present value of 164 years. This R/P ratio will decrease even more rapidly when clean coal technologies such as coal gasification and liquification are utilized instead of direct combustion.

1.4.4 Summary of Fossil Fuel Reserves

Even though there are widely differing views and estimates of the ultimately recoverable resources of fossil fuels, it is fair to say that they may last for around 50–150 years with a peak in production occurring much earlier. However, a big concern is the climatic threat of additional carbon that will be released into the atmosphere. According to the estimates from the IEA, if the present shares of fossil fuels are maintained up to 2030 without any carbon sequestration, a cumulative amount of approximately 1000 gigatons of carbon will be released into the atmosphere (based on Figure 1.7). This is especially troublesome in view of the fact that the present total cumulative emissions of about 300 gigatons of carbon have already raised serious concerns about global climate change.

1.4.5 Nuclear Resources

Increased use of nuclear power presents the possibility of additional carbon-free energy use and its consequent benefit for the environment. However, there are significant concerns about nuclear waste and other environmental impacts, the security of the fuel and the waste, and the possibility of their diversion for weapon production.

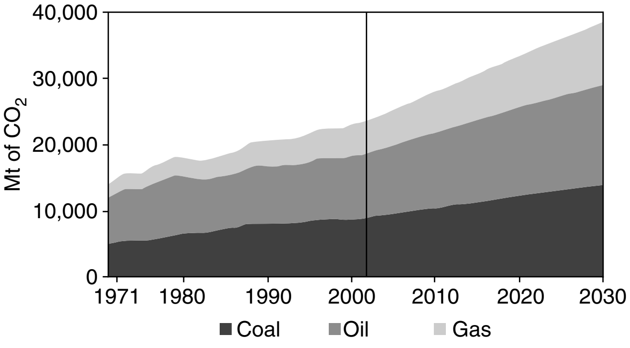


FIGURE 1.7 World energy-related CO_2 emissions by fuel. (Data and forecast from IEA, *World Energy Outlook*, IEA, Paris, 2004. With permission.)

According to the IAEA (2005) nuclear fission provided 16% of the electricity in the world in 2004, with a worldwide capacity of 368 GW. An additional 20 GW of nuclear power capacity was under construction during the same year. The IAEA also estimates that the worldwide nuclear power capacity will increase at an average rate of 0.5%–2.2% until 2030 (IAEA 2005). At present, uranium is used as the fissile material for nuclear power production. Thorium could also be used for nuclear fission; however, to date nobody has developed a commercial nuclear power plant based on thorium. Terrestrial deposits of both uranium and thorium are limited and concentrated in a few countries of the world. Estimates from the International Atomic Energy Agency (IAEA) and other sources show that the recoverable assured uranium reserves in the world are about 2.3 million tonnes to as much as 3.2 million tons (UNDP 2004). If additional estimated resources (not yet discovered) are also included, then the total resources become 5.1 million tons (UNDP 2004). Additionally, there are nonconventional uranium resources, such as sea water which contains about 3 parts per billion uranium and some phosphate deposits (more than half of them in Morocco) which contain about 100 parts per million uranium. These resources are potentially huge; however, their cost effective recovery is not certain.

Generating 1 TWh of electricity from nuclear fission requires approximately 22 tonnes of uranium (UNDP 2004). Based on the 2004 world capacity of 368 GW and an average annual growth rate of 2%, the present known uranium reserves of 2.3–3.2 million tonnes will last until 2030–2037. If all of the estimated (discovered and undiscovered) reserves of 5.1 million tonnes are considered, they will be used up by 2050. This estimate does not consider regeneration of spent fuel. At present, nuclear fuel regeneration is not allowed in the United States. However, that law could be changed in the future. Development of breeder reactors could increase the time period much further. Nuclear fusion could potentially provide a virtually inexhaustible energy supply; however, it is not expected to be commercially available in the foreseeable future.

1.4.6 Present Status and Potential of Renewable Energy (RE)

According to the data in Table 1.3, 13.3% of the world's total primary energy supply came from RE in 2003. However, almost 80% of the RE supply was from biomass (Figure 1.8), and in developing countries it is mostly converted by traditional open combustion, which is very inefficient. Because of its inefficient use, biomass resources presently supply only about 20% of what they could if converted by more efficient, already available technologies. As it stands, biomass provides only 11% of the world total primary energy, which is much less than its real potential. The total technologically sustainable biomass energy potential for the world is 3–4 TW_e (UNDP 2004), which is more than the entire present global electrical generating capacity of about 3 TW_e.

In 2003, shares of biomass and hydropower in the total primary energy mix of the world were about 11% and 2%, respectively. All of the other renewables, including solar thermal, solar PV, wind, geothermal, and ocean combined, provided only about 0.5% of the total primary energy. During the same year, biomass combined with hydroelectric resources provided more than 50% of all the primary

TABLE 1.3 2003 Fuel Shares in World Total Primary Energy Supply

Source	Share (%)
Oil	34.4
Natural Gas	21.2
Coal	24.4
Nuclear	6.5
Renewables	13.3

Source: Data from IEA, *World Energy Outlook*, IEA, Paris, 2004. With permission.

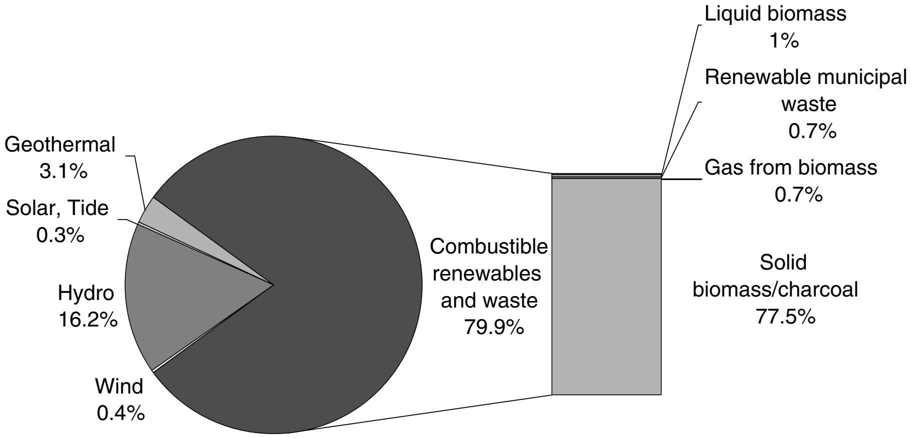


FIGURE 1.8 2003 resource shares in world renewable energy supply. (Data from IEA, *World Energy Outlook*, IEA, Paris, 2004. With permission.)

TABLE 1.4 Share of Renewable Energy (RE) in 2003 Total Primary Energy Supply (TPES) on a Regional Basis

Region	TPES	Renewables	Share of Renewables in TPES (%)
	MTOE	MTOE	
Africa	558.9	279.9	50.1
Latin America	463.9	135.5	29.2
Asia	1224.4	400	32.7
India	553.4	218	39.4
China	1425.9	243.4	17.1
Non-OECD[a] Europe	103.5	9.7	9.4
Former U.S.S.R.	961.7	27.5	2.9
Middle East	445.7	3.2	0.7
OECD	5394.7	304.7	5.6
U.S.A.	2280.8	95.3	4.2
World	10,578.7	1403.7	13.3

[a] OECD, Organization for Economic Cooperation and Development.
Source: From IEA, *Renewables Information*, IEA, Paris, 2005. With permission.

TABLE 1.5 Electricity from RE in 2002

Energy Source	2002	
	TWh	(%)
Hydropower	2610	89
Biomass	207	7
Wind	52	2
Geothermal	57	2
Solar	1	0
Tide/Wave	1	0
Total	2927	100

Source: Data from IEA, *World Energy Outlook*, IEA, Paris, 2004. With permission.

energy in Africa, 29.2% in Latin America, and 32.7% in Asia (Table 1.4; IEA 2005). However, biomass is used very inefficiently for cooking in these countries. Such use has also resulted in significant health problems, especially for women.

The total share of all renewables for electricity production in 2002 was about 17%, a vast majority (89%) of it being from hydroelectric power (Table 1.5).

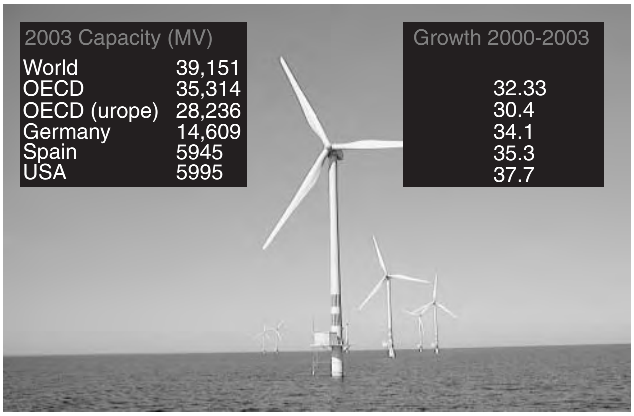
1.4.7 Wind Power

Wind-energy technology has progressed significantly over the last two decades. The technology has been vastly improved and capital costs have come down to as low as $1000 per kW. At this level of capital costs, wind power is already economical at locations with fairly good wind resources. Therefore, the average annual growth in worldwide wind energy capacity from 2000 to 2003 was over 30% (Figure 1.9) and it continued to grow at that rate in 2004 and 2005. The average growth in the United States over the same period was 37.7%. The total worldwide installed wind power capacity that was 39 GW in 2003 (Figure 1.9), reached a level of 59 GW in 2005 (WWEA 2006). The total theoretical potential for onshore wind power for the world is around 55 TW with a practical potential of at least 2 TW (UNDP 2004), which is about two-thirds of the entire present worldwide generating capacity. The offshore wind energy potential is even larger.

1.4.8 Solar Energy

The amount of sunlight striking the Earth's atmosphere continuously is 1.75×10^5 TW. Considering a 60% transmittance through the atmospheric cloud cover, 1.05×10^5 TW reaches the Earth's surface continuously. If the irradiance on only 1% of the Earth's surface could be converted into electric energy with a 10% efficiency, it would provide a resource base of 105 TW, whereas the total global energy needs for 2050 are projected to be about 25–30 TW. The present state of solar energy technologies is such that solar-cell efficiencies have reached over 20% and solar thermal systems provide efficiencies of 40%–60%. With the present rate of technological development, these solar technologies will continue improving, thus bringing the costs down, especially with the economies of scale.

Solar PV panels have come down in cost from about $30/W to about $3/W in the last three decades. At $3/W panel cost, the overall system cost is around $6/W, which is still too high to compete with other resources for grid electricity. However, there are many off-grid applications where solar PV is already cost-effective. With net metering and governmental incentives, such as feed-in laws and other policies,



2003 Capacity (MV)	
World	39,151
OECD	35,314
OECD (urope)	28,236
Germany	14,609
Spain	5945
USA	5995

Growth 2000-2003
32.33
30.4
34.1
35.3
37.7

FIGURE 1.9 World wind-energy installed capacity and growth rates. (Data from IEA, *World Energy Outlook*, IEA, Paris, 2004. With permission.)

TABLE 1.6 Growth in Photovoltaics (PV) Demand (2000–2003)

Region	Percent Increase 2000–2003 (%)
OECD	32
OECD (Europe)	41.1
Germany	51.1

even grid-connected applications such as building-integrated PV (BIPV) have become cost-effective. As a result, the worldwide growth in PV production has averaged over 30% per year from 2000 to 2003, with Germany showing the maximum growth of over 51% (Table 1.6; Figure 1.10).

Solar thermal power using concentrating solar collectors was the first solar technology that demonstrated its grid power potential. A 354 MW_e solar thermal power plant has been operating continuously in California since 1988. Progress in solar thermal power stalled after that time because of poor policy and lack of R&D. However, the last five years have seen a resurgence of interest in this area and a number of solar thermal power plants around the world are under construction. The cost of power from these plants (which is so far in the range of 12–16 U.S. cents/kWh) has the potential to go down to 5 U.S. cents/kWh with scale-up and creation of a mass market. An advantage of solar thermal power is that thermal energy can be stored efficiently and fuels such as natural gas or biogas may be used as backup to ensure continuous operation. If this technology is combined with power plants operating on fossil fuels, it has the potential to extend the time frame of the existing fossil fuels.

Low temperature solar thermal systems and applications have been well developed for quite some time. They are being actively installed wherever policies favor their deployment. Figure 1.11 gives an idea of the rate of growth of solar thermal systems in the world (ESTIF 2000). Just in 2003, over 10 MW_{th} solar collectors were deployed around the world, a vast majority of those being in China (Figure 1.12).

1.4.9 Biomass

Although theoretically harvestable biomass energy potential is on the order of 90 TW, the technical potential on a sustainable basis is on the order of 8–13 TW or 270–450 exajoules/year (UNDP 2004). This potential is 3–4 times the present electrical generation capacity of the world. It is estimated that by 2025, even municipal solid waste (MSW) alone could generate up to 6 exajoules/year (UNDP 2004).

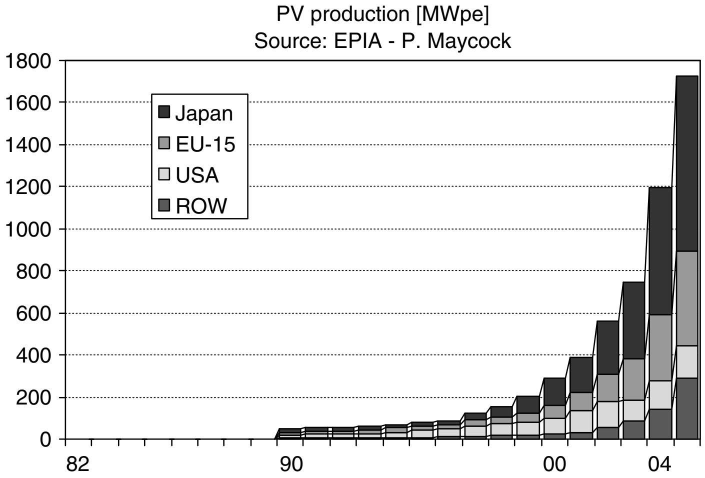


FIGURE 1.10 World solar PV production, 1990–2005 (MWp). (From Maycock, P., PV News Annual Review of the PV Market, 2006, http://www.epia.org. With permission.)

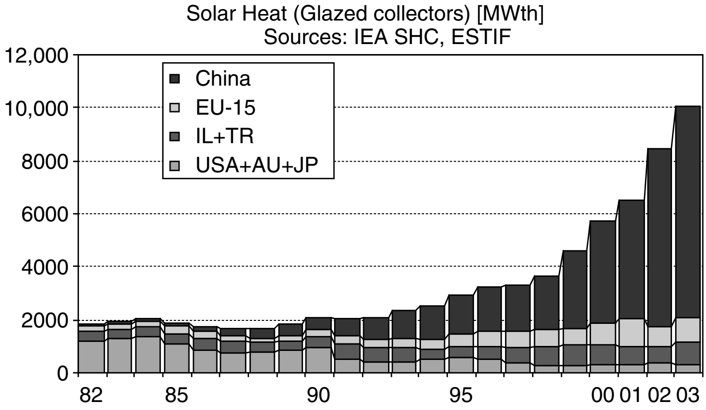


FIGURE 1.11 Deployment of solar heat (glazed) collectors (MW_{th}).

The biggest advantage of biomass as an energy resource is its relatively straightforward transformation into transportation fuels. Biofuels have the potential to replace as much as 75% of the petroleum fuels in use for transportation in the U.S.A. today (Worldwatch Institute 2006). This is especially important in view of the declining oil supplies worldwide. Biofuels will not require additional infrastructure development. Therefore, development of biofuels is being viewed very favorably by governments around the world. Biofuels, along with other transportation options such as electric vehicles and hydrogen, will help diversify the fuel base for future transportation. Figure 1.13 shows that global ethanol production more than doubled between 2000 and 2005. Biodiesel production grew almost fourfold, although it started from a much smaller base. In 2005, the world ethanol production had reached about 36 billion liters per year, whereas biodiesel production topped 3.5 billion liters during the same year. Table 1.7 shows the top five countries producing these fuels.

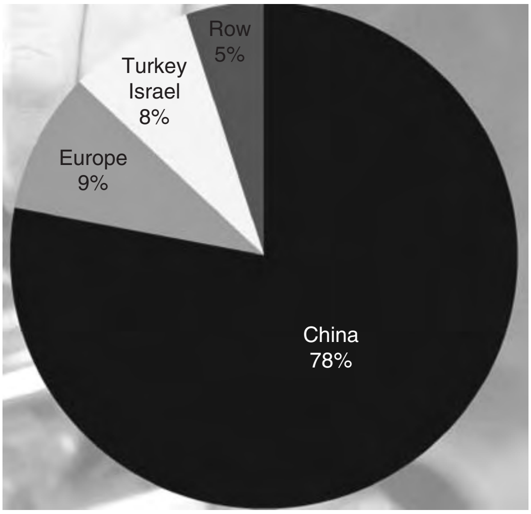


FIGURE 1.12 Worldwide distribution of solar thermal collector markets. (From ESTIF, *Solar Thermal Markets in Europe—Trends and Statistics for 2004*, European Solar Thermal Industry Federation, Brussels, Belgium, 2005. With permission.)

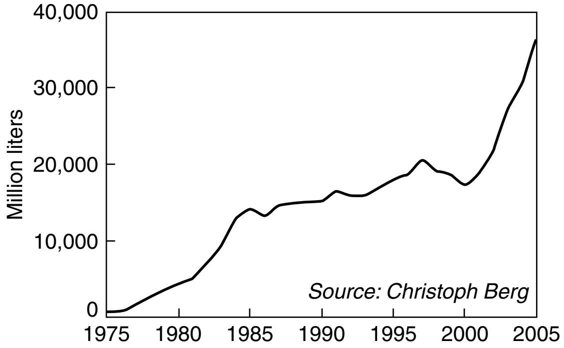


FIGURE 1.13 World fuel ethanol production, 1975–2005. (From Worldwatch, Biofuels for Transportation—Global Potential and Implications for Sustainable and Energy in the 21st Century, Report prepared for the German Federal Ministry for Food, Agriculture and Consumer Protection, Worldwatch Institute, Washington, DC, 2006. With permission.)

The present cost of ethanol production ranges from about 25 Euro cents to about 1 Euro per gasoline equivalent liter, as compared to the wholesale price of gasoline that is between 40 and 60 Euro cents per liter (Figure 1.14). Biodiesel costs, on the other hand, range between 20 Euro cents to 65 Euro cents per liter of diesel equivalent (Figure 1.15). Figure 1.16 shows the feedstocks used for these biofuels. An important consideration for biofuels is that the fuel not be produced at the expense of food while there are people going hungry in the world. This would not be of concern if biofuels were produced from municipal solid waste (MSW).

According to the Worldwatch report, a city of 1 million people produces about 1800 tonnes of MSW and 1300 tonnes of organic waste every day that, using the present-day technology, could produce enough fuel to meet the needs of 58,000 persons in the United States, 360,000 in France, and nearly 2.6 million in China at current rates of per capita fuel use (Worldwatch Institute 2006).

1.4.10 Summary of RE Resources

By definition, the term *reserves* does not apply to renewable resources. Therefore, we need to look at the annual potential of each resource. Table 1.8 summarizes the resource potential and the present costs and the potential future costs for the most important renewable resources.

TABLE 1.7 Top Five Ethanol and Biodiesel Producers in the World

	Ethanol Production (million liters/year)
Brazil	16,500
U.S.A.	16,230
China	2000
European Union	900
India	300
	Diesel Production (million liters/year)
Germany	1920
France	511
U.S.A.	290
Italy	227
Austria	83

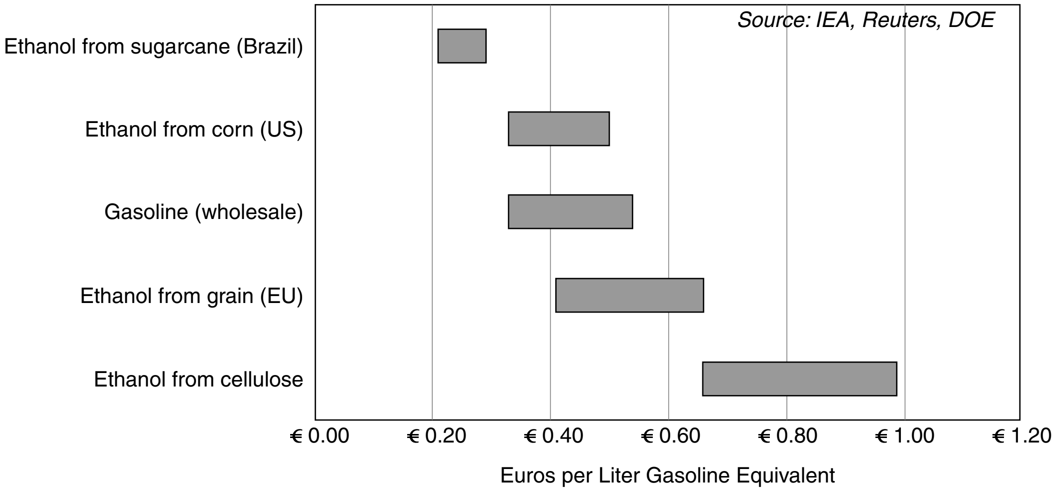


FIGURE 1.14 Cost ranges for ethanol and gasoline production, 2006. (From Worldwatch, Biofuels for Transportation—Global Potential and Implications for Sustainable Energy in the 21st Century, Report prepared for the German Federal Ministry for Food, Agriculture and Consumer Protection, Worldwatch Institute, Washington, DC, 2006. With permission.)

As in the case of other new technologies, it is expected that cost competitiveness of the RE technologies will be achieved with R&D, scale-up, commercial experience and mass production. The experience curves in Figure 1.17 show industry-wide cost reductions in the range of 10%–20% for each cumulative doubling of production for wind power, PV, ethanol, and gas turbines (UNDP 2004). Similar declines can be expected in solar thermal power and other renewable technologies. As seen from Figure 1.17, wind energy technologies have already achieved market maturity, and PV technologies are well on their way. Even though concentrating solar thermal power (CSP) is not shown in this figure, a GEF report estimates

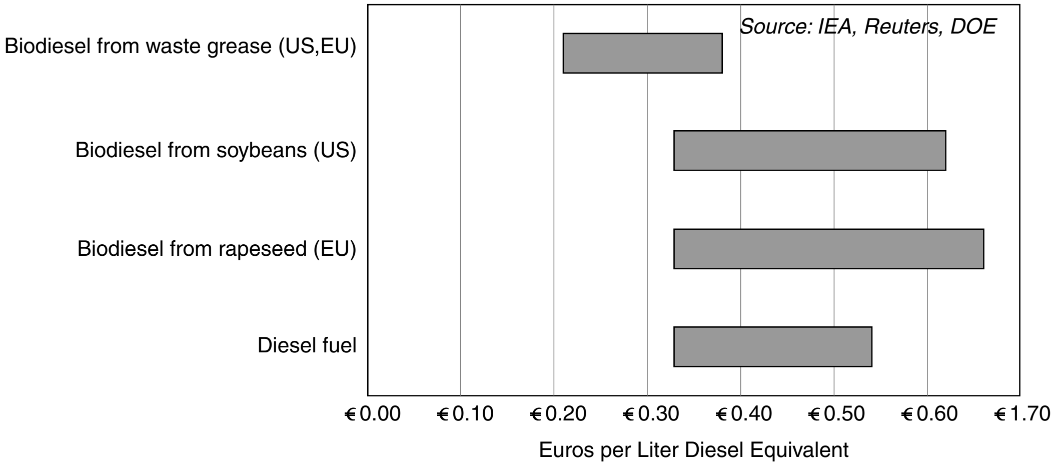


FIGURE 1.15 Cost ranges for biodiesel and diesel production, 2006. (From Worldwatch, Biofuels for Transportation—Global Potential and Implications for Sustainable and Energy in the 21st Century, Report prepared for the German Federal Ministry for Food, Agriculture and Consumer Protection, Worldwatch Institute, Washington, DC, 2006. With permission.)

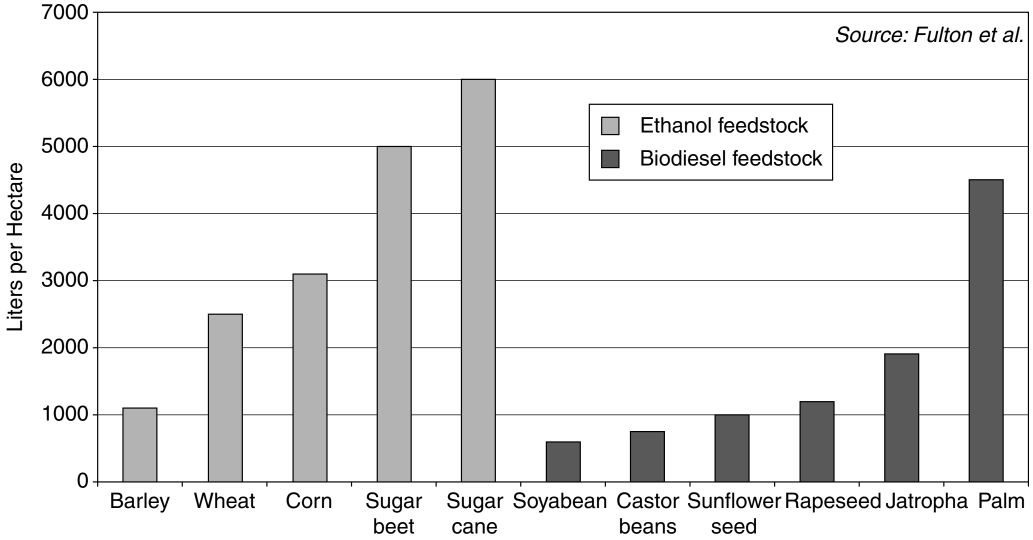


FIGURE 1.16 Biofuel yields of selected ethanol and biodiesel feedstocks. (From Worldwatch, Biofuels for Transportation—Global Potential and Implications for Sustainable and Energy in the 21st Century, Report prepared for the German Federal Ministry for Food, Agriculture and Consumer Protection, Worldwatch Institute, Washington, DC, 2006. With permission.)

that CSP will achieve the cost target of about $0.05/kWh by the time it has an installed capacity of about 40 GW (GEF 2005). As a reference point, wind power achieved that capacity milestone in 2003.

1.5 Role of Energy Conservation

Energy conservation can and must play an important role in future energy strategy, because it can ameliorate adverse impacts on the environment rapidly and economically. Figure 1.18 and Figure 1.19 give an idea of the potential of energy efficiency improvements. Figure 1.18 shows that per capita energy consumption varies by as much as a factor of three between the U.S.A. and some European countries with almost the same level of human development index (HDI). Even taking just the OECD European countries combined, the per capita energy consumption in the U.S.A. is twice as much. It is fair to assume that the per capita energy of the United States could be reduced to the level of OECD Europe of 4.2 kW by a combination of energy efficiency improvements and changes in the transportation infrastructure. This is significant because the U.S.A. uses about 25% of the energy of the whole world. The present per capita energy consumption in the U.S.A. is 284 GJ, which is equivalent to about 9 kW per person, whereas the average for the whole world is 2 kW. The Board of Swiss Federal Institutes of Technology has developed a vision of a 2-kW-per-capita society by the middle of the century (UNDP 2004). The vision is technically feasible. However, achieving this vision will require a combination of increased R&D on energy efficiency and policies that encourage conservation and use of high efficiency systems. It will also require some structural changes in the transportation systems. According to the 2004 World Energy Assessment by UNDP, a reduction of 25%–35% in primary energy in the industrialized countries is achievable cost effectively in the next 20 years, without sacrificing the level of energy services. The report also concluded that similar reductions of up to 40% are cost effectively achievable in the transitional economies and more than 45% in developing economies. As a combined result of efficiency improvements and structural changes such as increased recycling, substitution of energy intensive materials, etc., energy intensity could decline at a rate of 2.5% per year over the next 20 years (UNDP 2004).

TABLE 1.8 Potential and Status of RE Technologies

Technology	Annual Potential	Operating Capacity 2005^{a,b}	Investment Costs U.S.$ per kW^{b}	Current Energy Cost	Potential Future Energy cost
Biomass Energy	276–446 EJ total or 8–13 TW MSW ∼6 EJ				
Electricity		∼44 GW	500–6000/kW$_{e}$	3–12 c/kWh	3–10 c/kWh
Heat		∼225 GW$_{th}$	170–1000/kW$_{th}$	1–6 c/kWh	1–5 c/kWh
Ethanol		∼36 bln L	170–350/kW$_{th}$	25–75 c/L(ge)^{c}	6–10 $/GJ
Biodiesel		∼3.5 bln L	500–1000/kW$_{th}$	25–85 c/L(de)^{d}	10–15 $/GJ
Wind Power	55 TW theoretical 2 TW practical	59 GW	850–1700	4–8 c/kWh	3–8 c/kWh
Solar Energy	>100 TW				
Photovoltaics		5.6 GW	5000–10,000	25–160 c/kWh	5–25 c/kWh
Thermal power		0.4 GW	2500–6000	12–34 c/kWh	4–20 c/kWh
Heat			300–1700	2–25 c/kWh	2–10 c/kWh
Geothermal	600,000 EJ useful resource base 5000 EJ economical in 40–50 years				
Electricity		9 GW	800–3000	2–10 c/kWh	1–8 c/kWh
Heat		11 GW$_{th}$	200–2000	0.5–5 c/kWh	0.5–5 c/kWh
Ocean Energy					
Tidal	2.5 TW	0.3 GW	1700–2500	8–15 c/kWh	8–15 c/kWh
Wave	2.0 TW		2000–5000	10–30 c/kWh	5–10 c/kWh
OTEC	228 TW		8000–20,000	15–40 c/kWh	7–20 c/kWh
Hydroelectric	1.63 TW theoretical				
Large	0.92 TW econ.	690 GW	1000–3500	2–10 c/kWh	2–10 c/kWh
Small		25 GW	700–8000	2–12 c/kWh	2–10 c/kWh

[a] GW$_{e}$, gigawatt electrical power.

[b] GW$_{th}$, gigawatt thermal power.

[c] ge, gasoline equivalent liter.

[d] de, diesel equivalent liter.

Sources: Data from UNDP, *World Energy Assessment: Energy and the Challenge of Sustainability*, 2004, updated from other sources: Worldwatch Institute. 2006. *Biofuels for Transportation—Global Potential and Implications for Sustainable and Energy in the 21st Century*. Worldwatch Institute. Washington, DC, " Biofuels for Transportation—Global Potential and Implications for Sustainable andenergy in the 21st Century", Report prepared for the German Federal Ministry for Food, Agriculture and Consumer Protection, Worldwatch Institute, Wash., DC; World Wind Energy Association Bulletin, 2006, http://www.wwindea.org; EPIA, Photovoltoaic Barometer, http://www.epia.org; World Geothermal Power Generation 2001-[blc1]2005, GRC Bulletin, International Energy Annual, USEIA, 2006.

The summary of the economic energy efficiency potentials in North America up to the year 2010 are shown in Table 1.9. It is apparent that the greatest energy savings potential is in the transportation industry, followed by residential heating. The sources in the right-hand column refer to references in the United Nations study. In addition to the item cited in Table 1.9, it is believed that large energy savings are possible in office equipment, such as computers and communication. A similar estimate for the economic energy efficiency potential for Western Europe for the years 2010 and 2020 is presented in Table 1.10, where the resource references refer to the bibliography in Jochem (2000). Similar estimates for the energy saving potential in Japan, Asia and Latin America are presented in the same reference.

Improving energy efficiency across all sectors of the economy should become a worldwide objective (Energy Commission 2004). It should be noted, however, that free market price signals may not always be sufficient to effect energy efficiency. Hence, legislation on the state and/or national level for energy efficiency standards for equipment in the residential and commercial sector may be necessary. There is considerable debate whether incentives or mandates are the preferred way to improved energy efficiency.

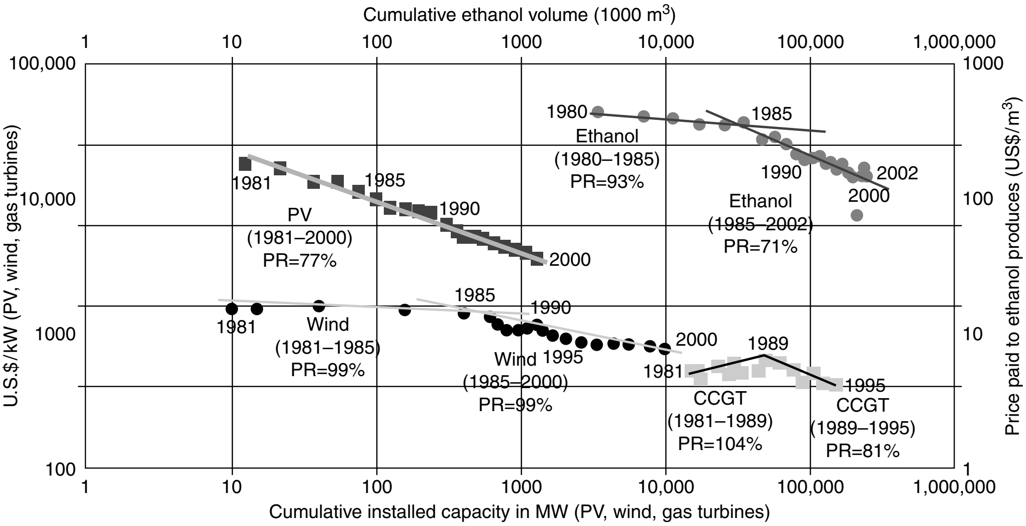


FIGURE 1.17 Experience curves for wind, PV, ethanol, and gas turbines. (Adapted from UNDP, *World Energy Assessment: Energy and the Challenge of Sustainability*, UNDP, 2004.)

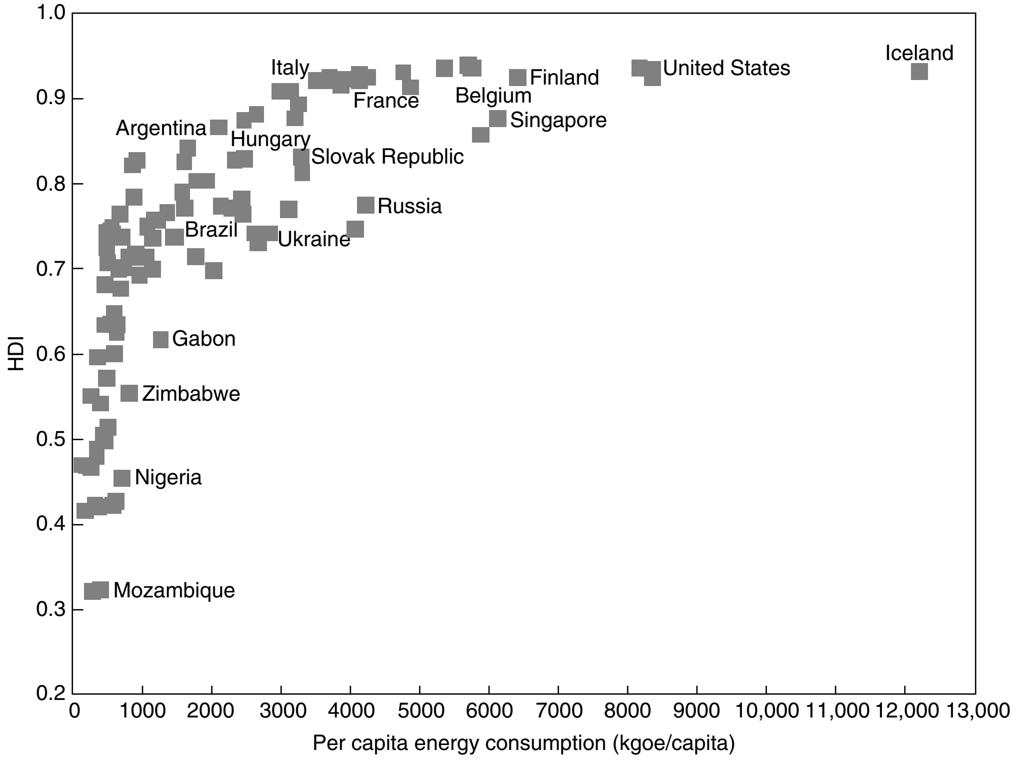
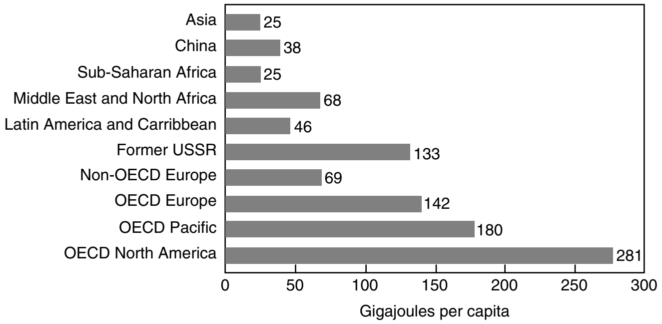


FIGURE 1.18 Relationship between Human Development Index (HDI) and per capita Energy Use, 1999–2000. (From UNDP, *World Energy Assessment: Energy and the Challenge of Sustainability*, UNDP, 2004. With permission.)



Notes: Asia excludes Middle East, China,and OECD countries;Middle East and North Africa comprises Algeria,Bahrain,Egypt,Iran,Iraq, Israel,Jordan,Kuwait,Lebanon,Libya,Moroco, Oman,Qatar,Saudi Arabia,Syria,Tunisia,United Arab Emirates and Yemen;Latin America and Caribbean excludes Mexico;OECD Pacific comprises Australia,Japan,Korea,and New Zealand;Former USSR comprises Armenia, Azerbaijan,Belarus,Estonia,Georgia,Kazakhstan, Kyrgyzstan,Latvia,Lithuania,Moldova,Russia, Tajikistan,Turkmenistan,Ukraine,and Uzbekistan,Non-OECD Europe consists of Albania,Bosnia and Herzegovina,Bulgaria, Croatia,Cyprus,Gilbraltar,Macedonia,Malta, Romaina,and Slovenia;OECD North America includes Mexico.

FIGURE 1.19 Per capita energy use by region (commercial and noncommercial), 2000. (From UNDP, *World Energy Assessment: Energy and the Challenge of Sustainability*, UNDP, 2004. With permission.)

Such measures may be necessary because surveys indicate that consumers consistently rank energy use and operating costs quite low on the lists of attributes they consider when purchasing an appliance or construct a building. Incentives may be the preferred option provided they induce decision makers to take appropriate action.

In the United States, by the year 2004, national efficiency standards were in effect for a variety of residential and commercial appliances. Updated standards will take effect in the next few years for several more products. Figure 1.20 shows the projected energy savings from upgraded standards for products installed in the years 2010–2020. Outside the United States, over 30 countries have also adopted

TABLE 1.9 Economic Energy Efficiency Potentials in North America, 2010

Sector and Area	Economic Potential (percent)		Energy Price Level Assumed	Base Year
	United States[a]	Canada		
Industry				
Iron and steel	4–8	29	United States: scenario for price developments[b]	United States: 1995
Aluminium (primary)	2–4			
Cement	4–8			
Glass production	4–8			Canada: 1990
Refineries	4–8	23	Canada: price scenario by province[c]	
Bulk chemicals	4–9	18		
Pulp and paper	4–8	9		
Light manufacturing	10–18			
Mining	n.a.	7		
Industrial minerals	n.a.	9		
Residential				
Lighting	53		United States: scenario for price developments	United States: 1995
Space heating	11–25			

(continued)

TABLE 1.9 (***Continued***)

Sector and Area	Economic Potential (percent)		Energy Price Level Assumed	Base Year
	United States[a]	Canada		
Space cooling	16			
Water heating	28–29			Canada: 1990
Appliances	10–33		Canada: price scenario	
Overall		13		
Commercial and public				
Space heating	48		United States: scenario for price developments	United States: 1995
Space cooling	48			
Lighting	25			
Water heating	10–20			Canada:1990
Refrigeration	31		Canada: price scenario	
Miscellaneous	10–33			
Overall	n.a.	9		
Transportation				
Passenger cars	11–17		United States: scenario for price developments	United States: 1997
Freight trucks	8–9			
Railways	16–25			
Aeroplanes	6–11			Canada: 1990
Overall	10–14	3	Canada: price scenario	

[a] Industrial energy efficiency potentials in the United States reflect an estimated penetration potential under different conditions based on the Interlaboratory Working Group on Energy Efficient and Low-Carbon Technologies (1997). There are no separate estimates available for the economic potential. The economic potential under business-as-usual fuel price developments is estimated at 7 percent in energy-intensive industries and 16 percent in light industries.

[b] The Inter-Laboratory Working Group study (1997) used price scenarios for 1997–2010 to estimate the potential for energy efficiency improvement, based on the *Annual Energy Outlook 1997* scenario (EIA, 1996). The scenario assumes a 1.2 percent annual increase in oil prices from 1997 levels.

[c] For comparison; in 2010 light fuel oil price are \$6–8 a gigajoule at the 1999 exchange rate (Jaccard and Willis Energy Services, 1996).

Source: From UNDP (United Nations Development Programme), World energy assessment: Energy and the challenge of sustainability, New York, 2004.

minimum energy performance standards. These measures have been shown to be economically attractive and can provide an appreciable reduction in adverse environmental impacts.

This handbook describes energy efficiency improvements achievable with available technologies. The challenge is to adopt policies that accelerate the adoption of these technologies all over the world.

1.6 Forecast of Future Energy Mix

As explained above, it is clear that oil production will peak in the near future and will start declining thereafter. Since oil comprises the largest share of world energy consumption, a reduction in availability of oil will cause a major disruption unless other resources can fill the gap. Natural gas and coal production may be increased to fill the gap, with the natural gas supply increasing more rapidly than coal.

TABLE 1.10 Economic Energy Efficiency Potentials in Western Europe, 2010 and 2020

Sector and Technological Area	Economic Potential (percent)[a]		Energy Price Level Assumed	Base Year
	2010	2020		
Industry				
Iron and steel, coke ovens	9–15	13–20	1994	1995
Construction materials	5–10	8–15	1997	1997
Glass production	10–15	15–25	1997	1997
Refineries	5–8	7–10	1995	1997
Basic organic chemicals	5–10		1997	1996
Pulp and paper		50	1996	1997
Investment and consumer goods	10–20	15–25	1994	1995
Food	10–15		1997	1997
Cogeneration in industry		10–20	1997	1997
Residential				
Existing buildings				
Boilers and burners	15–20	20–25	Today's prices	1997
Building envelopes	8–12	10–20	Today's prices	1995
New buildings		20–30	Today's prices	1995
Electric appliances	20–30	35–45	1997	1997
Commercial, public, and agriculture				
Commercial buildings	10–20	30	8–13 c/kWh	1995
Electricity	10–25	20–37	4–10 c/kWh	1997
Heat		15–25	Today's prices	1998
Public buildings		30–40	7–15 c/kWh	1992
Agriculture and forestry		15–20	Today's prices	
Horticulture		20–30	Today's prices	
Decentralised cogeneration		20–30	Today's prices	1995
Office equipment		40–50	1995	1995
Transportation				
Cars	25		Today's prices	1995
Door-to-door integration	4			1995
Modal split of freight transport		3[b]		1995
Trains and railways		20	Today's prices	1999
Aircraft, logistics	15–20	25–30	Today's prices	1998

[a] Assumes a constant structure or use of the sector or technology considered.

[b] Refers to the final energy use of the entire sector.

However, that will hasten the time when natural gas production also peaks. Additionally, any increase in coal consumption will worsen the global climate change situation. Although CO_2 sequestration is feasible, it is doubtful that there will be any large-scale application of this technology for existing plants. However, all possible measures should be taken to sequester CO_2 from new coal-fired power plants. Presently, there is a resurgence of interest in nuclear power. However, it is doubtful that nuclear power alone will be able to fill the gap. Forecasts from IAEA show that nuclear power around the world will grow at a rate of 0.5%–2.2% over the next 25 years (IAEA 2005). This estimate is in the same range as that of IEA.

Based on this information it seems logical that the RE technologies of solar, wind and biomass will not only be essential but will hopefully be able to fill the gap and provide a clean and sustainable energy future. Although, wind and photovoltaic power have grown at rates of over 30%–35% per year over the last few years, this growth rate is based on very small existing capacities for these sources. There are many

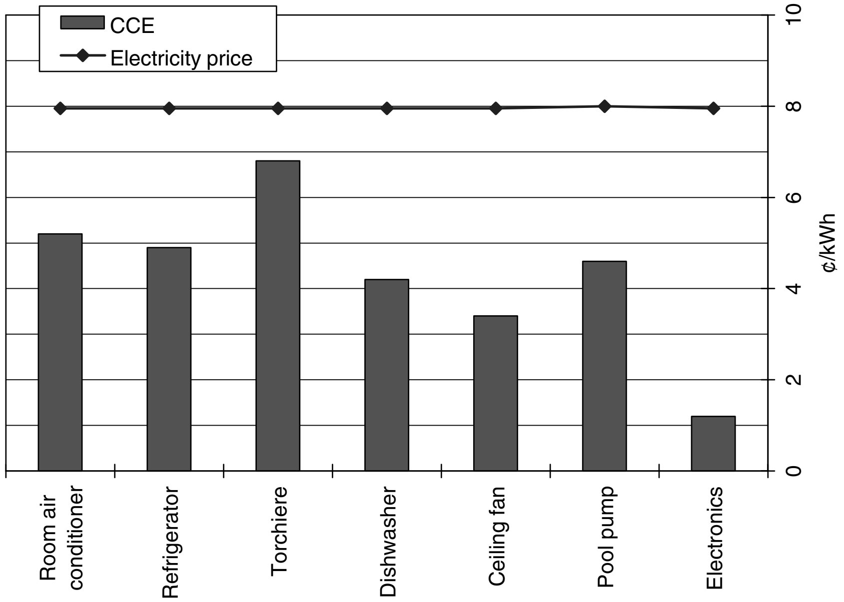


FIGURE 1.20 Comparison of cost of conserved energy for 2010 standards to projected electricity price in the residential sector.

differing views on the future energy mix. The IEA estimates (Figure 1.21) that the present mix will continue until 2030 (IEA 2004).

On the other hand, the German Advisory Council on Global Change (WBGU) estimates that as much as 50% of the world's primary energy in 2050 will come from RE, increasing to 80% by 2100 (Figure 1.22; WBGU 2003). However to achieve that level of RE use by 2050 and beyond will require worldwide effort on the scale of a global Apollo Project.

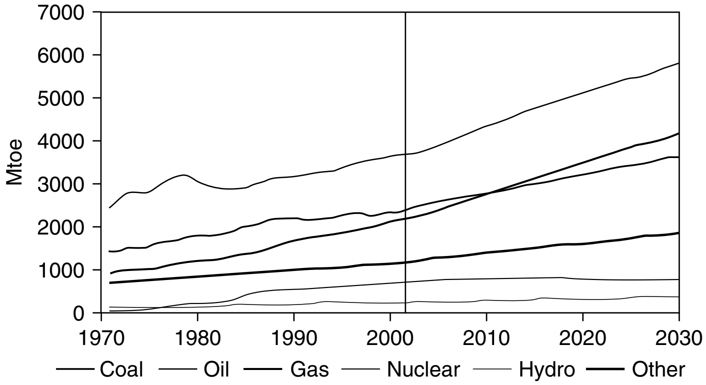


FIGURE 1.21 **(See color insert following page 774.)** World primary energy demand by fuel types according to IEA. (From IEA, *World Energy Outlook*, IEA, Paris, 2004.)

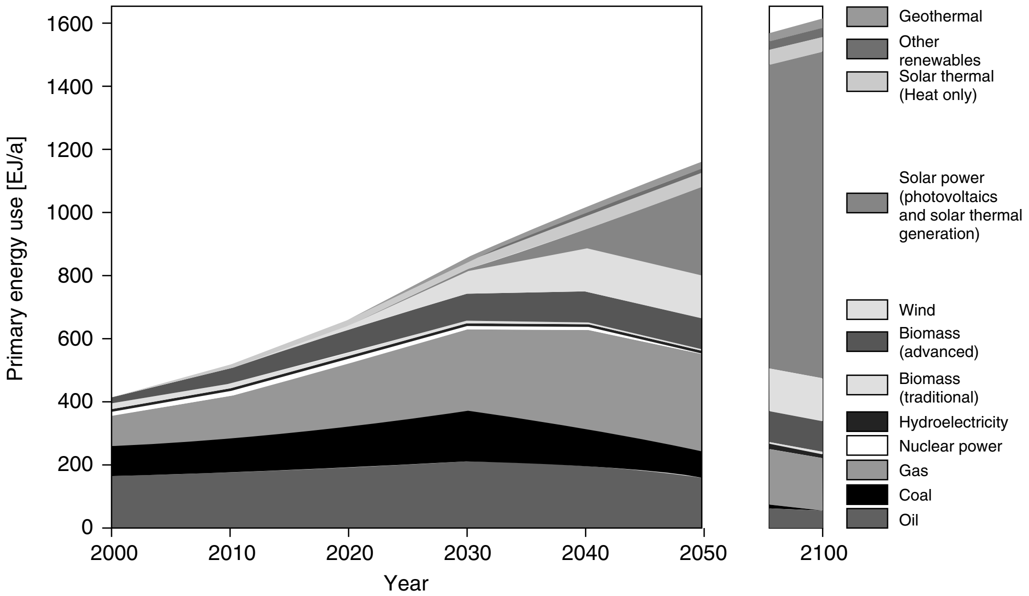


FIGURE 1.22 **(See color insert following page 774.)** The global energy mix for year 2050 and 2100 according to WBGU. (From WBGU, World in Transition—Towards Sustainable Energy Systems, German Advisory Council on Global Change, Berlin, 2003.)

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