ENERGY PRIMER

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Energy Primer

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CONTENTS

B.1. Introduction

This Energy Primer introduces concepts and terms used in the energy-related chapters of this Second Assessment Report that deal with adaptation to and mitigation of climate change. Some of the more important terms also are defined in the Glossary. The Energy Primer also describes some of the more commonly used energy units; most measurements, including energy, are expressed in the International System of Units (SI) and SI-derived units.

Section B.2 describes the global energy system and documents 1990 energy-consumption patterns and carbon dioxide (CO_2) emissions. Thereafter, the concept of energy efficiency is introduced and 1990 global efficiencies are provided along with some estimates of maximum efficiencies that could be achieved under ideal conditions, indicating the theoretical efficiency improvement potential. Section B.3 describes and documents the historical development of energy consumption and associated CO_2 emissions for the world and for major regions. It concludes with a comparison of historical and current energy consumption, estimates of fossil and nuclear energy reserves and resources, and potentials of renewable energy sources. Section B.4 of this Energy Primer gives a brief introduction to the following chapters, which assess energy-related mitigation and adaptation options and measures.

B.2. Energy Systems

B.2.1. The Global Energy System

An *energy system* comprises an energy supply sector and energy end-use. The energy supply sector consists of a sequence of elaborate and complex processes for extracting energy resources, converting these into more desirable and suitable forms of energy, and delivering energy to places where the demand exists. The end-use part of the energy system provides energy services such as cooking, illumination, comfortable indoor climate, refrigerated storage, transportation, and consumer goods. The purpose, therefore, of the energy system is the fulfillment of demand for energy services. Figure B-1 illustrates schematically the architecture of an energy system as a series of

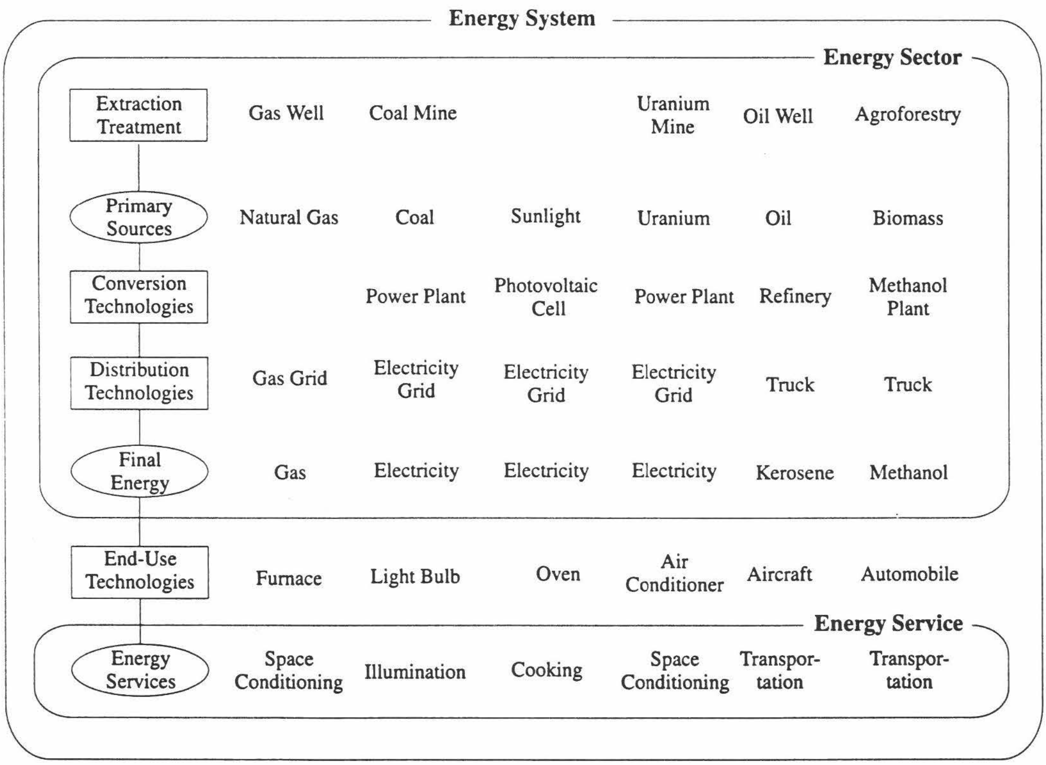

Figure B-1: The energy system: schematic diagram with some illustrative examples of the energy sector and energy end-use and services. The energy sector includes energy extraction, treatment, conversion, and distribution of final energy. The list is not exhaustive, and the links shown between stages are not "fixed" (e.g., natural gas is also used to generate electricity, and coal is not used exclusively for electricity generation). Source: Adapted from Rogner, 1994.

linked stages connecting various energy conversion and transformation processes that ultimately result in the provision of goods and services. A number of examples are given for energy extraction, treatment, conversion, distribution, end-use (final energy), and energy services in the energy system. The technical means by which each stage is realized have evolved over time, providing a mosaic of past evolution and future options.

Primary energy is the energy that is embodied in resources as they exist in nature: the chemical energy embodied in fossil fuels (coal, oil, and natural gas) or biomass, the potential energy of a water reservoir, the electromagnetic energy of solar radiation, and the energy released in nuclear reactions. For the most part, primary energy is not used directly but is first converted and transformed into electricity and fuels such as gasoline, jet fuel, heating oil, or charcoal.

Final energy is the energy transported and distributed to the point of final use. Examples include gasoline at the service station, electricity at the socket, or fuelwood in the barn. The next energy transformation is the conversion of final energy in end-use devices, such as appliances, machines, and vehicles, into *useful energy,* such as work and heat. Useful energy is measured at the crankshaft of an automobile engine or an industrial electric motor, by the heat of a household radiator or an industrial boiler, or by the luminosity of a light bulb. The application of useful energy provides *energy services,* such as a moving vehicle, a warm room, process heat, or light.

Energy services are the result of a combination of various technologies, infrastructures (capital), labor (know-how), materials, and energy carriers. Clearly, all these input factors carry a price tag and, within each category, are in part substitutable for one another. From the consumer's perspective, the important issues are the quality and cost of energy services. It often matters little what the energy carrier or the source of that carrier is. It is fair to say that most consumers are often unaware of the "upstream" activities of the energy system. The energy system is service-driven (i.e., from the bottom up), whereas energy flows are driven by resource availability and conversion processes (from the top down). Energy flows and driving forces interact intimately. Therefore, the energy sector should never be analyzed in isolation: It is not sufficient to consider only how energy is supplied; the analysis also must include how and for what purposes energy is used.

Figure B-2 illustrates schematically the major energy and carbon flows through the global energy system across the main stages of energy transformation, from primary energy to energy services. Energy and carbon estimates represent global averages in 1990. For definitions of energy and carbon-emissions units, see Boxes B-1 and B-2.

In 1990, 385 EJ of primary energy produced 279 EJ of final energy delivered to consumers, resulting in an estimated 112 EJ of useful energy after conversion in end-use devices. The delivery of 112 EJ of useful energy left 273 EJ of rejected energy. Most rejected energy is released into the environment as

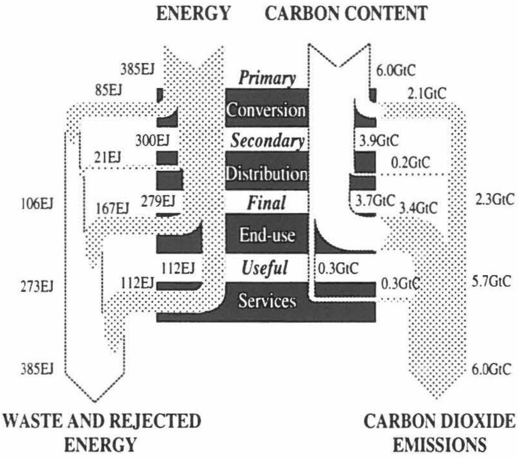

Figure B-2: Major energy and carbon flows through the global energy system in 1990, EJ and Gt C [(billion tons) or Pg C (10^{15} grams) elemental carbon]. Carbon flows do not include biomass. Sources: Marland *et al.*, 1994; IEA, 1993; Marland and Rotty, 1984; Nakicenovic *et al.*, 1993; WEC, 1992a.

low-temperature heat, with the exception of some losses and wastes such as the incomplete combustion of fuels.

More than half of the anthropogenic greenhouse gas (GHG) emissions originate from the energy system (both in terms of mass and in terms of radiative forcing). The predominant gas is CO_2, which represents more than half of the increase in radiative forcing from anthropogenic GHG sources. The majority of this CO_2 arises from the use of fossil fuels, which in turn make up about 75% of the total energy use. The global energy consumption of 385 EJ in 1990 was small compared with the solar radiation of about 5.4 million EJ intercepted annually by Earth. Although small in relation to natural energy flows, the emissions of energy-related GHGs create a danger of anthropogenic interference with Earth's radiative balance (energy budget).

The carbon content of fossil energy in 1990 was about 6 (±0.5) Gt C [(billion tons) or Pg C (10^{15} grams) elemental carbon], of which about 2.3 Gt C were emitted by the energy sector during conversion to fuels and electricity and distribution to final use. The remainder, about 3.7 Gt C, was emitted at the point of end-use. Included are 0.3 Gt C that were extracted from fossil sources without contributing directly to net carbon emissions. This carbon was embodied in durable hydrocarbon-based materials such as plastics, asphalt, lubricants, and pharmaceuticals. The carbon flows in Figure B-2 are simplifications because the carbon in fossil fuels is not completely oxidized to CO_2 during combustion. Eventually, however, most hydrocarbons and other combustion products containing carbon are converted to CO_2. There is some ambiguity concerning the amount of CO_2 emissions from feedstocks embodied in chemical products, as well as the unsustainable use of biomass. Carbon is released by the burning of biomass,

Box B-1. Energy Units and Scales

Energy is defined as the capacity to do work and is measured in joules (J), where 1 joule is the work done when a force of 1 newton (1 N = 1 kg m/s^2) is applied through a distance of 1 meter. Power is the rate at which energy is transferred and is commonly measured in watts (W), where 1 watt is 1 joule per second. Newton, joule, and watt are defined as units in the International System of Units (SI). Other units used to measure energy are toe (ton of oil equivalent; 1 toe = 41.87 x 10^9 J), used by the oil industry; tce (ton of coal equivalent; 1 tce = 29.31 x 10^9 J), used by the coal industry; and kWh (kilowatt-hours; 1 kWh = 3.6 x 10^6 J), used to measure electricity. Figure B-3 shows some of the commonly used units of energy and a few examples of energy consumption levels, along with the Greek names and symbols for factors to power of ten (e.g., exa equals 10^{18} and is abbreviated as E; in 1990, the global primary energy consumption was 385 EJ).

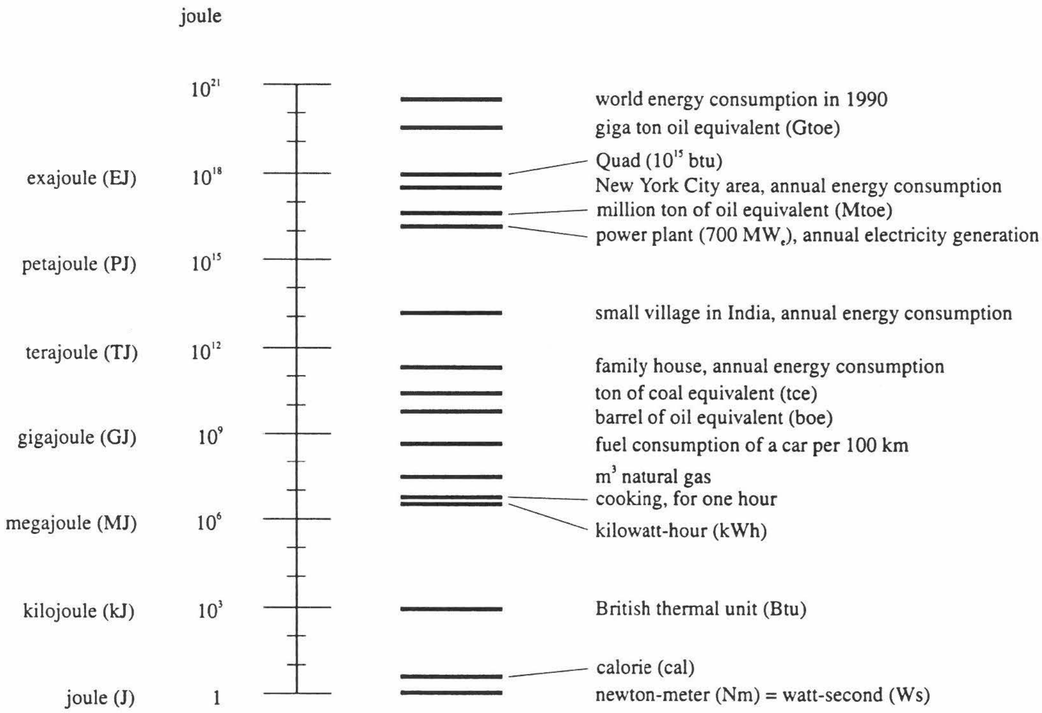

Figure B-3: Examples of some human energy needs and energy conversion devices, in joules, on a logarithmic scale. Sources: Adapted from Starr, 1971; Swedish National Encyclopedia, 1993.

including energy-related uses. Houghton and Skole (1990) estimate the latter to result in gross emissions of 0.7 Gt C per year. The extent of annual net emissions from nonfossil CO_2 is difficult to determine due to forest regrowth and the fact that the majority of biomass use is renewable. For simplification, we assume that feedstocks lead to CO_2 emissions—because even materials like asphalt and durable plastics will eventually be oxidized over a very long time—and that all biomass used as a source of energy is renewable and therefore does not result in net CO_2 emissions.

The 1990 global economic output is estimated at about US$21 x 10^{12} (World Bank, 1993; UN, 1993); therefore, the average energy intensity was about 18 MJ/US$, and energy-related carbon intensity was about 250 g C/US$. In 1990, the average person consumed about 73 GJ of energy and emitted about 1.1 t C (tons carbon or Mg C).

B.2.2. Energy Efficiency

Energy is conserved in every conversion process or device. It can neither be created nor destroyed, but it can be converted from one form into another. This is the first law of thermodynamics. For example, energy in the form of electricity entering

Box B-2. CO_2 Emission Factors

CO_2 emissions are measured in tons (10^6 grams) of elemental carbon. For example, in 1990, global CO_2 emissions were 6 Gt C [(billion tons) or Pg C (10^{15} grams) of elemental carbon]. In the literature, CO_2 emissions also are reported as the mass of the actual molecule (1 kg C corresponds to 3.67 kg of CO_2).

Table B-1: *Carbon-emissions factors for some primary energy sources, in kg C/GJ.*

		OECD/IPCC 1995 (1)	Literature Range	Sources
Wood	HHV	–	26.8–28.4	
	LHV		28.1–29.9	(5),(3)
Peat	HHV	–	30.3	(3)
	LHV	28.9		
Coal (bituminous)	HHV	–	23.9–24.5	(2),(3)
	LHV	25.8	25.1–25.8	(2),(3)
Crude Oil	HHV	–	19.0–20.3	(3),(4)
	LHV	20.0	20.0–21.4	(3),(4)
Natural Gas	HHV	–	13.6–14.0	(2),(5)
	LHV	15.3	15.0–15.4	(2),(5)

Notes: HHV is the higher heating value and LHV the lower; the difference is that HHV includes the energy of condensation of the water vapor contained in the combustion products.
Sources:
(1) OECD/IPCC, 1991 and 1995.
(2) Marland and Pippin, 1990.
(3) Grubb, 1989.
(4) Marland and Rotty, 1984.
(5) Ausubel *et al.*, 1988.

an electric motor results in the desired output—say, kinetic energy of the rotating shaft to do work—and losses in the form of heat as the undesired byproduct caused by electric resistance, magnetic losses, friction, and other imperfections of actual devices. The energy entering a process equals the energy exiting. Energy efficiency is defined as the ratio of the desired (usable) energy output to the energy input. In the electric-motor example, this is the ratio of the shaft power to the energy input electricity. In the case of natural gas for home heating, energy efficiency is the ratio of heat energy supplied to the home to the energy of the natural gas entering the furnace. This definition of energy efficiency is sometimes called *first-law efficiency*.

A more efficient provision of energy services not only reduces the amount of primary energy required but, in general, also reduces adverse environmental impacts. Although efficiency is an important determinant of the performance of the energy system, it is not the only one. In the example of a home furnace, other considerations include investment, operating costs, lifetime, peak power, ease of installation and operation, and other technical and economic factors. For entire energy systems, other considerations include regional resource endowments, conversion technologies, geography, information, time, prices, investment finance, operating costs, age of infrastructures, and know-how.

The overall efficiency of an energy system depends on the individual process efficiencies, the structure of energy supply and conversion, and the energy end-use patterns. It is the result of compounding the efficiencies of the whole chain of energy supply, conversion, distribution, and end-use processes. The weakest link in the analysis of the efficiency of various energy chains is the determination of energy services and their quantification, mostly due to the lack of data about end-use devices and actual patterns of their use.

In 1990, the global efficiency of converting primary energy sources to final energy forms, including electricity, was about 72% (279 EJ over 385 EJ—see Figure B-2). The efficiency of converting final energy forms into useful energy is lower, with an estimated global average of 40% (Nakicenovic *et al.*, 1990;

Gilli *et al.*, 1995). The resulting average global efficiency of converting primary energy to useful energy, then, is the product of the above two efficiencies, or 29%. Because detailed statistics for most energy services do not exist and many rough estimates enter the efficiency calculations, the overall efficiency of primary energy to services reported in the literature spans a wide range, from 15 to 30% (Olivier and Miall, 1983; Ayres, 1989; Wall, 1990; Nakicenovic *et al.*, 1990; Schaeffer and Wirtshafter, 1992; and Wall *et al.*, 1994).

How much energy is needed for a particular energy service? The answer to this question is not so straightforward. It depends on the type and quality of the desired energy service; the type of conversion technology; the fuel, including the way the fuel is supplied; and the surroundings, infrastructures, and organizations that provide the energy service. Initially, energy-efficiency improvements can be achieved in many instances without elaborate analysis through common sense, good housekeeping, and leak-plugging practices. Obviously, energy service efficiencies improve as a result of sealing leaking window frames or installing a more efficient furnace. If the service is transportation—getting to and from work, for example—using a transit bus jointly with other commuters is more energy-efficient than taking individual automobiles. After the easiest improvements have been made, however, the analysis must go far beyond energy accounting.

Here the concept that something may get lost or destroyed in every energy device or transformation process is useful. This "something" is called "availability," which is the capacity of energy to do work. Often the availability concept is called "exergy."[1]

The following example should help clarify the difference between energy and exergy. A well-insulated room contains a small container of kerosene surrounded by air. The kerosene is ignited and burns until the container is empty. The net result is a small temperature increase of the air in the room ("enriched" with the combustion products). Assuming no heat leaks from the room, the total quantity of energy in the room has not changed. What has changed, however, is the quality of energy. The initial fuel-air combination has a greater potential to perform useful tasks than the resulting slightly warmer air mixture. For example, one could use the fuel to generate electricity or operate a motor vehicle. The ability of a slightly warmed room to perform any useful task other than space conditioning is very limited. In fact, the initial potential of the fuel-air combination or the "exergy" has been largely lost.[2] Although energy is conserved, exergy is destroyed in all real-life energy conversion processes. This is what the second law of thermodynamics expresses.

Another, more technical, example should help clarify the difference between first-law (energy) and second-law (exergy) efficiencies. Furnaces used to heat buildings are typically 70 to 80% efficient, with the latest, best-performing condensing furnaces operating at efficiencies greater than 90%. This may suggest that little energy savings should be possible, considering the high first-law efficiencies of furnaces. Such a conclusion is incorrect. The quoted efficiency is based on the specific process being used to operate the furnace—combustion of fossil fuel to produce heat. Because the combustion temperatures in a furnace are significantly higher than those desired for the energy service of space heating, the service is not well-matched to the source, and the result is an inefficient application of the device and fuel. Rather than focusing on the efficiency of a given technique for the provision of the energy service of space heating, one needs to investigate the theoretical limits of the efficiency of supplying heat to a building based on the actual temperature regime between the desired room temperature and the heat supplied by a technology. The ratio of theoretical minimum energy consumption for a particular task to the actual energy consumption for the same task is called exergy or *second-law* (of thermodynamics) *efficiency*.

Consider an example: Providing a temperature of 30°C to a building while the outdoor temperature is 4°C requires a theoretical minimum of one unit of energy input for every 12 units of heat energy delivered to the indoors. To provide 12 units of heat with an 80% efficient furnace, however, requires 12/0.8, or 15, units of heat. The corresponding second-law efficiency is the ratio of ideal to actual energy use (i.e., 1/15 or 7%).

The first-law efficiency of 80% gives the misleading impression that only modest improvements are possible. The second-law efficiency of 7% says that a 15-fold reduction in final heating energy is theoretically possible.[3] In practice, theoretical maxima cannot be achieved. More realistic improvement potentials might be in the range of half of the theoretical limit. In addition, further improvements in the efficiency of supplying *services* are possible by task changes—for instance, reducing the thermal heat losses of the building to be heated via better insulated walls and windows.

What is the implication of the second law for energy efficiencies? First of all, it is not sufficient to account for energy-in

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[1] Exergy is defined as the maximum amount of energy that under given (ambient) thermodynamic conditions can be converted into any other form of energy; it is also known as availability or work potential (WEC, 1992b). Therefore, exergy defines the minimum theoretical amount of energy required to perform a given task.

[2] An alternative example: In terms of energy, 1 kWh of electricity and the heat contained in 43 kg of 20°C water are equal (i.e., 3.6 MJ). At ambient conditions, it is obvious that 1 kWh electricity has a much larger potential to do work (e.g., to turn a shaft or to provide light) than the 43 kg of 20°C water. See also Moran, 1989.

[3] For example, instead of combusting a fossil fuel, Goldemberg *et al.* (1988) give the example of a heat pump, which extracts heat from a local environment (outdoor air, indoor exhaust air, groundwater) and delivers it into the building. A heat pump operating on electricity can supply 12 units of heat for 3 to 4 units of electrical energy. The second-law efficiency improves to 25–33% for this particular task— still considerably below the theoretical maximum efficiency. Not accounted for in this example, however, are energy losses during electricity generation. Assuming a modern gas-fired, combined-cycle power plant with 50% efficiency, the overall efficiency gain is still a factor of two compared with a gas furnace heating system.

versus energy-out ratios without due regard for the quality difference (i.e., the exergy destroyed in the process). Minimum exergy destruction means an optimal match between the energy service demanded and the energy source. Although a natural-gas heating furnace may have an energy efficiency of close to 100%, the exergy destruction may be very high, depending on the temperature difference between the desired room temperature and the temperature of the environment. The second-law efficiency, defined as exergy-out over exergy-in, in this natural-gas home heating furnace example is some 7%—that is, 93% of the original potential of doing useful work (exergy) of the natural gas entering the furnace is lost. Here we have a gross mismatch between the natural-gas potential to do useful work and the low-temperature nature of the energy service, namely space conditioning.

There are many difficulties and definitional ambiguities involved in estimating the exergy efficiencies for comprehensive energy source-to-service chains or entire energy systems. There are many examples for the analysis of individual conversion devices; for instance, losses around a thermal power plant are described in Yasni and Carrington (1989). A few attempts have also been made to analyze energy systems efficiencies to useful energy or even to energy services. All indicate that primary-to-service (second-law or exergy) efficiencies are as low as a few percent. AIP (1975) and Olivier and Miall (1983) were among the first to give detailed assessments of end-use exergy efficiencies, including service efficiencies. Ayres (1989) calculates an overall primary exergy to service efficiency of 2.5% for the United States. Wall (1990) estimates a primary-to-useful exergy efficiency in Japan of 21%, and Wall *et al.* (1994) calculate a primary-to-useful exergy efficiency of less than 15% for Italy. Schaeffer and Wirtshafter (1992) estimate a primary-to-useful energy efficiency of 32% and an exergy efficiency of 23% for Brazil. Other estimates include Rosen (1992) for Canada, and Özdogan and Arikol (1995) for Turkey. Estimates of global and regional primary-to-service exergy efficiencies vary from ten to as low as a few percent (Gilli *et al.*, 1990, 1995; Nakicenovic *et al.*, 1990, 1993).

The theoretical potential for efficiency improvements is very large; current energy systems are nowhere close to the maximum levels suggested by the second law of thermodynamics. However, the full realization of this potential is impossible. Friction, resistance, and similar losses never can be totally avoided. In addition, there are numerous barriers and inertias to be overcome, such as social behavior, vintage structures, financing of capital costs, lack of information and know-how, and insufficient policy incentives.

The principal advantage of second-law efficiency is that it relates actual efficiency to the theoretical (ideal) maximum. Although this theoretical maximum can never be reached, low-exergy efficiencies identify those areas with the largest potentials for efficiency improvement. For fossil fuels, this suggests the areas that also have the highest emission-mitigation potentials.

B.3. Energy Use, CO_2 Emissions, and Energy Resources

B.3.1. Past and Present Energy Use

Global primary energy consumption has grown at an average annual rate of about 2% per year for almost 2 centuries—doubling, on average, about every 3 decades. This estimate includes all sources of commercial energy and fuelwood. There is a considerable variation in energy consumption growth rates over time and between different regions. For example, the global fossil energy consumption grew at 5% per year between 1950 and 1970, 3.3% annually between 1970 and 1990, and only 0.3% per year between 1990 and 1994. Emissions and other environmental effects of energy supply and end-use increased at somewhat slower rates than primary energy consumption.

Figure B-4 shows global annual primary energy consumption by source since 1860; Figure B-5 shows the relative shares of each source in total consumption. With the emergence of the coal age and steam power, global primary energy use evolved from a reliance on traditional energy sources, such as fuelwood, to fossil energy. Subsequently, coal was replaced by oil as the dominant primary energy source. Energy conversion also changed fundamentally with internal combustion, electricity generation, steam and gas turbines, and chemical and thermal energy conversion. The dynamics of structural changes in the global energy system, illustrated in Figure B-5, can be characterized by relatively slow rates of change, which are typical for infrastructures. It took about half a century before coal was replaced by crude oil as the dominant global energy source. At the global level, the "time constant" for fundamental energy transitions has been on the order of 50 years. At the regional level and for individual energy technologies and devices, the characteristic time constants are usually shorter, as a result of faster capital turnover, among other factors.

Much of the historical increase in global primary energy consumption has occurred in the more developed countries. About

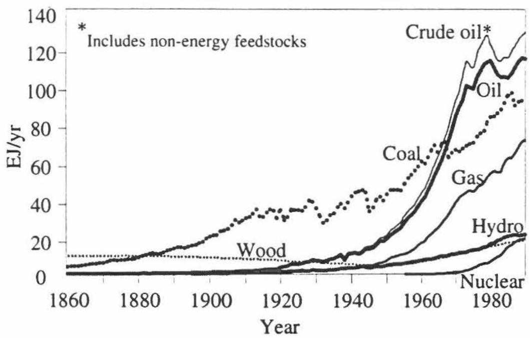

Figure B-4: Global primary energy consumption by source, and total in EJ/yr (data for crude oil include non-energy feedstocks). Sources: BP, various volumes; IEA, 1993; Marchetti and Nakicenovic, 1979.

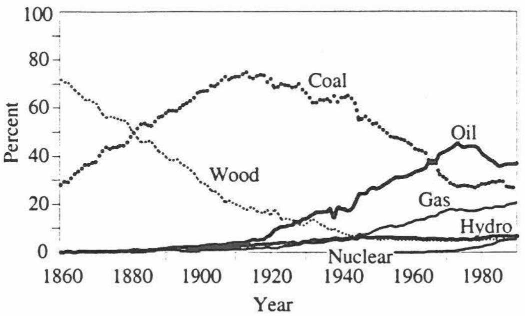

Figure B-5: Shares of energy sources in total global primary energy consumption, in percent of the total.

25% of the world's population consume almost 80% of the global energy. Cumulative consumption is even more unevenly distributed: About 85% of all energy used to date has been consumed by less than 20% of the cumulative global population (measured in cumulative person-years) since 1860. The differences in current per capita commercial energy consumption are more than a factor of 20 between the highest (North America) and the lowest (Africa) energy-consuming regions in the world—but more than a factor of 500 between individual countries. Another important difference is in the structure of energy supply, especially the strong reliance on traditional and noncommercial sources of energy in the developing countries (Hall, 1991).

Table B-2 shows the 1990 energy balance for the world from primary to final energy consumption, by energy carrier and sector. Crude oil is the dominant primary energy source in the world, accounting for 33% of the total, followed by coal and natural gas with 24 and 18% shares, respectively. Hydropower and nuclear energy are regionally important; they contribute more than 19 and 15% to global electricity supply, respectively. About 13% of the final energy is delivered as electricity. The largest final energy share of 38% is taken by oil products, half of them being used in the transport sector and constituting 96% of all the energy needs in this sector. The largest final energy carrier in industry is coal at 30%, accounting for almost 70% of all the direct uses of coal. Two-thirds of primary coal is used for electricity generation. About 30% of natural gas is used for electricity generation; the rest is divided almost equally between industrial uses and those in the household, commercial, and agricultural sectors. Electricity is also almost equally divided between these end uses. Most traditional biomass is used locally, with little or no conversion, and is shown under the "other" sector category in Table B-2. Primary energy consumption is well-documented in both national and international statistics. An exception is the use of traditional noncommercial energy (biomass). Larger uncertainties surround sectoral disaggregations of final energy consumption, due to a lack of detailed statistics in many countries. The numbers on sectoral final energy use given in Table B-2 are estimates. In some cases, alternative estimates are presented in individual chapters that deal with sectoral energy issues.

The historical shifts from traditional energy sources and coal to crude oil and natural gas were accompanied by the development of elaborate conversion systems for the production of more suitable forms of final energy, such as electricity. These structural changes, together with improvements in the performance of individual energy technologies, have resulted in significant efficiency improvements. Efficiency improvements in converting primary sources to final and useful energy forms, along with economic structural change, have contributed to a reduction of specific primary energy needs for generating a unit of economic output, usually measured in terms of gross domestic product (GDP) or gross national product (GNP). This ratio is often called energy intensity. Figure B-6 illustrates the changes in energy intensity for a number of world regions and countries and shows that, on average, 1% less energy per year was required every successive year to generate a unit of economic output. Actual variations of energy intensities and their improvement rates are large—depending, for instance, on the

Table B-2: *Global energy consumption in 1990 by energy source and by sector, in EJ/yr.*

	Coal	Oil	Gas	Nuclear	Hydro[a]	Electricity	Heat	Biomass	Total
Primary	91	128	71	19	21	–	–	55	385
Final	36	106	41	–	–	35	8	53	279
Industry	25	15	22	–	–	17	4	3	86
Transport	1	59	0	–	–	1	0	0	61
Others	10	18	18	–	–	17	4	50	117
Feedstocks[b]	0	14	1	–	–	–	–	0	15

Notes: Primary energy is recovered or gathered directly from natural sources (e.g., mined coal, collected biomass, or harnessed hydroelectricity), then is converted into fuels and electricity (e.g., electricity, gasoline, and charcoal), resulting in final energy after distribution and delivery to the point of consumption.

Sources: IEA, 1993; Hall, 1991, 1993; UN, 1993; WEC, 1983, 1993a, 1993b; Nakicenovic *et al.*, 1993.

[a] Nuclear and hydropower electricity have been converted into primary thermal equivalent, with an average factor of 38.5% (WEC, 1983).

[b] Feedstocks represent non-energy use of hydrocarbons.

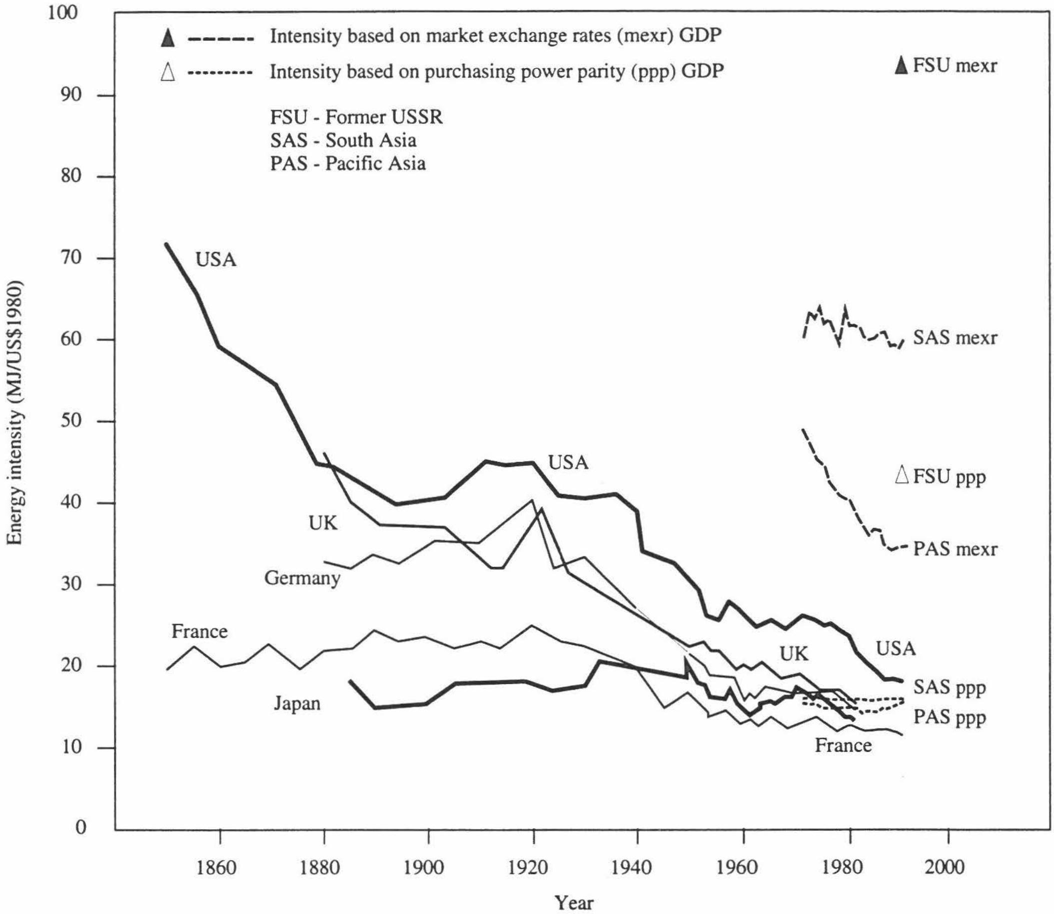

Figure B-6: Primary energy intensity (including wood and biomass) of value added in MJ per constant GDP in 1980 dollars [at market exchange rates (mexr) and purchasing power parities (ppp)]. Source: Grübler, 1991.

measure adopted to compare GDP between countries and regions, geographical factors, energy prices, and policies.

B.3.2. Past and Present CO_2 Emissions

CO_2 emissions from fossil energy consumption in 1990 are estimated at about 6.0 (±0.5) Gt C (Marland *et al.*, 1994; Subak *et al.*, 1993). This represents 70 to 90% of all anthropogenic sources of CO_2 in that year (IPCC, 1992).

Figure B-7 shows fossil energy CO_2 emissions by major world regions (emission factors are given in Box B-2). Developed countries contribute most to present global CO_2 emissions and also are responsible for most of the historical increase in concentrations. Although they are at lower absolute levels, emissions are growing more rapidly in developing countries than in developed regions. The largest single source of energy-related carbon emissions is coal, with about a 43% share, followed by oil with about 39%, and natural gas with 18%. Adding non-energy feedstocks reverses the shares to 40% for coal and 42% for oil. Due to the lack of data, these shares do not include energy-related deforestation or CO_2 emissions from unsustainable use of biomass.

Figure B-8 shows 1990 per capita CO_2 emissions in a number of world regions by source and relates these to the respective population size. Estimates of nonfossil sources of CO_2 are included.[4] The current levels of per capita fossil-fuel carbon

[4] Including CO_2 emissions from land-use changes such as deforestation (1.6±1 Gt C—IPCC, 1992). The extent of annual net emissions from nonfossil CO_2 sources is difficult to determine due to forest regrowth and the fact that the majority of biomass use is renewable.

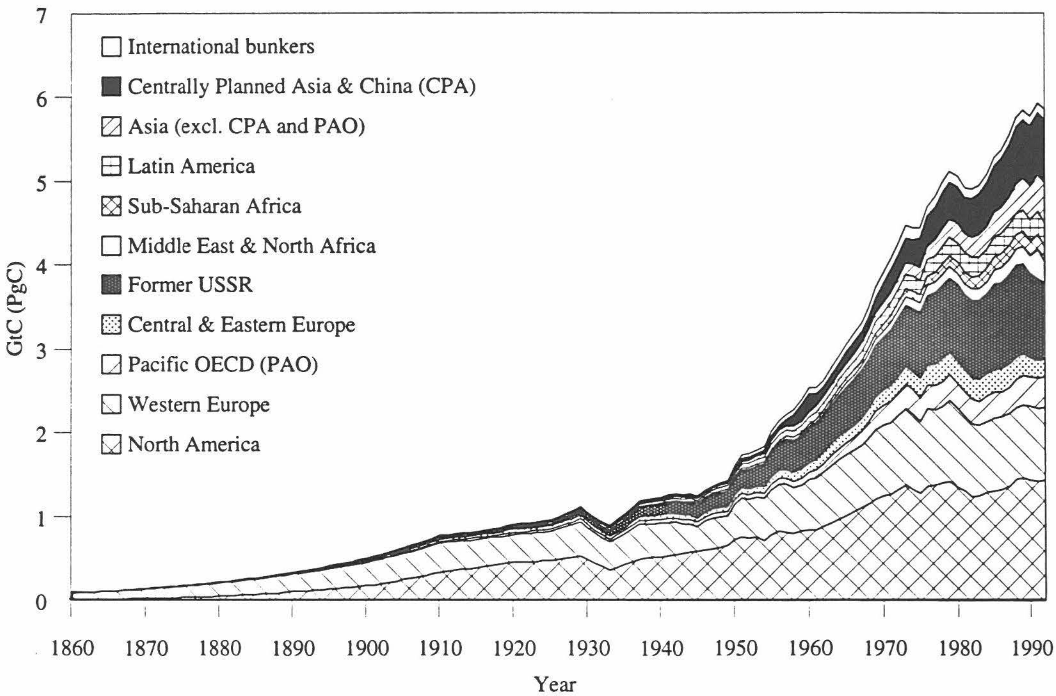

Figure B-7: Global energy-related CO_2 emissions by major world region in Gt C/yr (Pg C/yr). Sources: Keeling, 1994: Marland *et al.*, 1994; Grübler and Nakicenovic, 1992; Etemad and Luciani, 1991; Fujii, 1990; UN, 1952.

emissions in the world regions shown in Figure B-8 differ by a factor of 30. A persistent per capita emission gap remains after including carbon emissions from tropical deforestation, currently estimated to range between 0.6 and 2.6 Gt C/yr throughout the 1980s (IPCC, 1990, 1992; Ferreira and Marcondes, 1991; Houghton *et al.*, 1987).

The CO_2 emission intensity of both energy and economic activities is decreasing. Figure B-9 illustrates the extent of "decarbonization" in terms of the ratio of average carbon emissions per unit of primary energy consumed globally since 1860. The ratio has decreased due to the replacement of fuels with high carbon content, such as coal, by those with lower carbon content, such as natural gas, and by those with zero carbon content, such as nuclear power (see Figure B-5).[5] Energy development paths in different countries and regions have varied enormously and consistently over long periods. The overall tendency has been toward lower carbon intensities, although intensities are currently increasing in some developing countries. At the global level, the reduction in carbon intensity per unit value added has been about 1.3% per year since the mid-1800s—about 1.7% short of that required to offset the growth in global economic output of about 3% per year during that period (hence, global CO_2 emissions have grown at approximately 1.7%/yr).

B.3.3. Energy Reserves, Resources, and Potentials

Energy *occurrences* and their potential recoverability cannot be characterized by a simple measure or single numbers. They comprise quantities along a continuum in at least three, interrelated, dimensions: geological knowledge, economics, and technology. McKelvey (1972) proposed a commonly used diagram with a matrix structure for the classification along two dimensions: decreasing geological certainty of occurrence and decreasing economic recoverability.

Reserves are those occurrences that are identified and measured as economically and technically recoverable with current technologies and prices. *Resources* are those occurrences with

[5] It should be noted that so-called zero-carbon energy sources can result in some CO_2 and other GHG emissions, either because fossil energy is embodied in their construction materials (e.g., concrete in the structures of a nuclear power plant or a hydroelectric dam) or because fossil energy is required for operation and maintenance of energy facilities (e.g., gasoline and diesel vehicles). Some renewable sources also can entail CO_2 and other GHG emissions during operation. Examples include CO_2 emissions from geothermal; CH_4 emissions from anaerobic decay of biomass in flooded hydropower reservoirs; or CH_4, CO, and N_2O emissions from biomass burning.

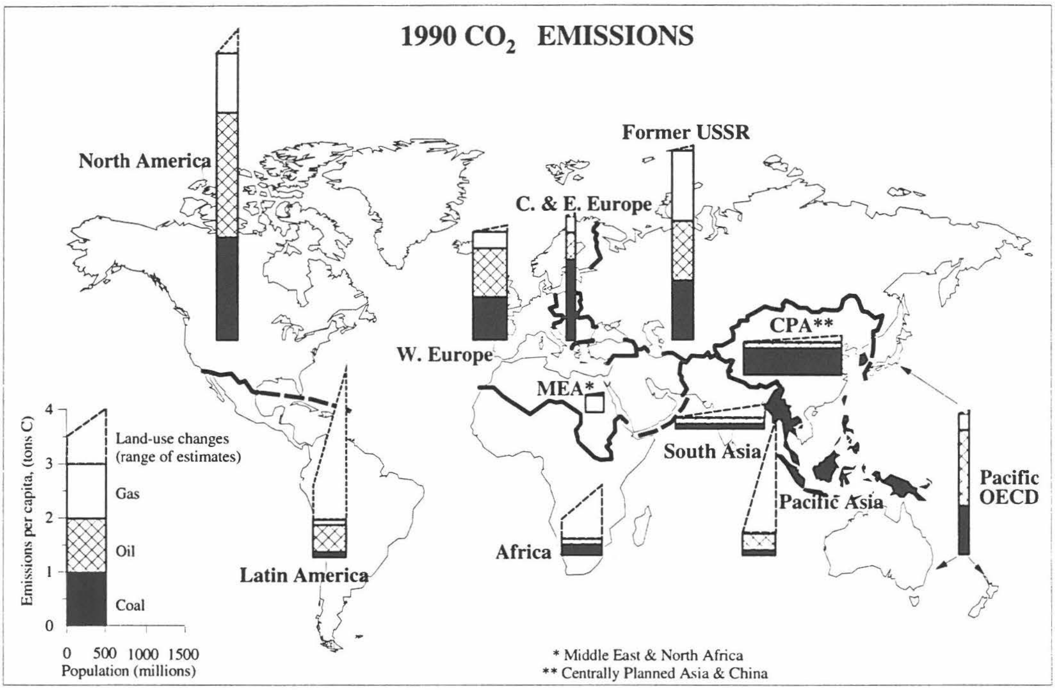

Figure B-8: 1990 per capita CO_2 emissions by region and source, fossil fuels, and range for biota sources (includes sustainable use of biomass that does not contribute to atmospheric concentration increase). Sources: IEA, 1993; Marland *et al.*, 1994; Nakicenovic *et al.*, 1993; Subak *et al.*, 1993; IPCC, 1990, 1992; Bos *et al.*, 1992; Houghton *et al.*, 1987.

less-certain geological and/or economic characteristics, but which are considered potentially recoverable with foreseeable technological and economic developments. The resource base includes both categories.[6] Additional quantities with unknown certainty of occurrence and/or with unknown or no economic significance in the foreseeable future are referred to here simply as "additional occurrences." For example, such additional occurrences include methane hydrates and natural uranium in seawater, both inferred to exist in large quantities but with unknown economic and/or technological means for extraction. Occurrences comprise all of the above three categories: reserves, resources, and additional occurrences.

Improved geological knowledge, both scientific and experimental (e.g., reservoir theories and exploration); improved technology; and changing prices have continuously served to increase the fossil energy resource base and have led to numerous large discoveries. Additions to reserves from resources have historically outpaced consumption. However, transfers from resources to reserves require investments. This adds a financial constraint on the expansion of reserves, so that from an economic point of view it makes little sense to invest in maintaining reserves for more than 20 years of production. For oil, this has indeed been the case. Therefore, there is a lot of exploration that still can be done but that has been deferred to the future for economic reasons. This is an important point when trying to understand energy reserves and why significant discoveries are still being made.

B.3.3.1. Fossil and Nuclear Reserves and Resources

Currently identified global fossil energy reserves are estimated to be about 50,000 EJ. This quantity is theoretically large enough to last 130 years at the 1990 level of global energy consumption of 385 EJ. It is five times larger than cumulative fossil energy consumption since the beginning of the coal era in the mid-19th century. Coal accounts for more than half of all fossil reserves. Table B-3 summarizes past and current consumption levels and estimates of global fossil and nuclear energy reserves, resources, and additional occurrences.

Estimates of resources and additional occurrences of fossil energy are much larger but more uncertain than reserves. Table B-3

[6] The fossil fuel resource-base estimates include potentially recoverable resources of coal, conventional oil, natural gas, unconventional oil (oil shale, tar sands, and heavy crude), and unconventional natural gas (gas in Devonian shales, tight sand formations, geopressured aquifers, and coal seams).

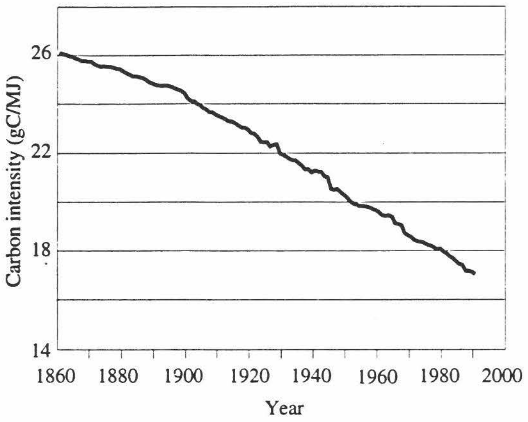

Figure B-9: Global decarbonization of energy since 1860 (including gross carbon emissions from fuelwood), in g C/MJ of primary energy. Source: Nakicenovic *et al.*, 1993.

shows the global fossil resource-base estimate to be about 186,000 EJ, with additional occurrences of almost 1 million EJ. Included in the conventional resources are estimates of ultimately recoverable conventional oil and gas resources remaining to be discovered at 95%, 50%, and 5% probability levels, ranging between from 1,800 and 5,500 EJ for oil and 2,700 and 10,900 EJ for gas (Masters *et al.*, 1991, 1994).

Methane resources are of particular interest because they have the lowest specific carbon emissions per unit energy of all fossil fuels. They are also of interest because methane is the second most important GHG associated with energy use and with anthropogenic activities in general. Because methane has a higher radiative forcing than CO_2 as a GHG, its climate effects are significantly reduced if it is oxidized into CO_2 (i.e., burned) instead of being released into the atmosphere. The reserves of unconventional gas are of the same magnitude as those for oil. The unconventional gas resource base is larger than that of unconventional oil, whereas the conventional resource bases are about the same. Additionally, there are large gas occurrences in the form of hydrates in permafrost areas and offshore continental-shelf sediments—in the range of 800,000 EJ (Kvenvolden, 1993; MacDonald, 1990).

The fossil resource base and additional occurrences are the ultimate global "carbon endowment" available to future generations, a number larger than 25,000 Gt C (Pg C). Fossil energy reserves correspond to 1,000 Gt C—exceeding the current carbon content of Earth's atmosphere (about 770 Gt C, or an

Table B-3: *Global fossil energy reserves, resources, and occurrences, in EJ.*

	Consumption[a]		**Reserves**	**Conventional Resources** Remaining to be Discovered at Probability[b]			**Unconventional Resources**			
	1860–1990	1990	**Identified**	95%	50%	5%	Currently Recoverable	Recoverable w/ Technological Progress	**Resource Base**[c]	**Additional Occurrence**
Oil										
Conventional	3343	128	6000	1800	2500	5500			8500	>10000
Unconventional	–	–	7100					9000	16100	>15000
Gas										
Conventional	1703	71	4800	2700	4400	10900			9200	>10000
Unconventional	–	–	6900				2200	17800	26900	>22000
Hydrates[d]	–	–								>800000
Coal	5203	91	25200				13900	86400	125500	>130000
Total	10249	290	50000	>4500	>6900	>16400	>16100	>113200	>186200	>987000
Nuclear[e]	212	19	1800		2300		4100	>6000	>14200	>1000000

Notes: All totals have been rounded; – = negligible amounts; blanks = data not available.
Sources: Nakicenovic *et al.*, 1993; WEC, 1992a; Grübler, 1991; MacDonald, 1990; Masters *et al.*, 1994; Rogner, 1990; BP, various volumes; BGR, 1989; Delahaye and Grenon, 1983.
[a] Grübler and Nakicenovic, 1992.
[b] Masters *et al.*, 1994.
[c] Resource base is the sum of reserves and resources. Conventional resources remaining to be discovered at probability of 50% are included for oil and gas.
[d] MacDonald, 1990.
[e] Natural uranium reserves and resources are effectively 60 times larger if fast breeder reactors are used. Calculated from natural uranium reserves and resources (OECD/NEA and IAEA, 1993) into thermal equivalent for once-through fuel cycle with average factor of 1,700 g per TJ thermal or 4,440 g natural uranium per TJ of electricity (16 Mg natural uranium per TWh_e electricity).

atmospheric concentration of 358 ppm in 1994). The resource base of conventional oil, gas, and coal, with some 3,500 Gt C, is about five times as large as the current atmospheric carbon content.

Uranium reserves, recoverable at costs less than US$130/kg, were evaluated at 3 million tons of natural uranium in January 1993 (OECD/NEA and IAEA, 1993). This corresponds to about 600 EJ of electricity—or about 1,800 EJ thermal equivalent if used in convertor reactors with a once-through fuel cycle (i.e., without reprocessing or final disposal of spent fuel) or to more than 100,000 EJ if used in fast breeder reactors (see Table B-3). In addition, some 4 million tons of natural uranium (corresponding to 2,300 EJ thermal) are known to exist; part of this supply is in countries where recovery costs have not been estimated. Uranium resources recoverable from unconventional ore bodies or as a byproduct amount to some 7 million tons of natural uranium (4,100 EJ thermal). Resources, estimated through geological assessment, amount to some 10 to 11 million tons of natural uranium (5,800 to 6,400 EJ thermal). Additional occurrences that cannot be exploited with current technologies include seawater, with an estimated natural uranium energy content exceeding one million EJ. Thorium reserves and resources are reported only for a few countries, and on that basis are estimated at 4 million tons. Geological information suggests that the resources may be much larger.

B.3.3.2. Renewable Energy Potentials and Natural Flows

In contrast to fossil energy sources, renewable energy forms such as solar, wind, and hydro can be either carbon-free or carbon-neutral. The sustainable use of biomass, for example, is carbon-neutral. Solar photovoltaic electricity generation is carbon-free. One must be careful, of course, to examine the full life cycle of the system when comparing the GHG implications of different energy systems because, for example, all energy systems currently rely on fossil fuels to construct devices, transport material, and dispose of waste.

Figure B-10 provides a schematic illustration of annual global energy flows without anthropogenic interference (Sørensen, 1979), and Table B-4 gives a summary of the annual (global) natural flows of renewable energy worldwide and their technical recovery potentials, as well as estimates for more practical potentials that could be achieved by 2020–2025 with current and near- to medium-term technologies and cost structures. The concept of technical potential can be used in a similar fashion as the concept of energy resources, and potentials by 2020 as the concept of energy reserves. The fundamental difference, of course, is that renewable potentials represent annual flows available, in principle, on a sustainable basis indefinitely, whereas fossil energy reserves and resources, although expanding in time, are fundamentally finite quantities. Life-cycle analyses remain important because although the energy flows are sustainable they still require materials like concrete and copper and the commitment of land and other resources. The renewable energy potentials identified in Table B-4 are theoretically large enough to provide the current primary energy needs for the world, and the technical potentials are large enough to cover most of the conceivable future growth of global energy demand.

Table B-4: *Global renewable energy potentials by 2020–2025, maximum technical potentials, and annual natural flows, in EJ thermal equivalent.*[a]

	Consumption[b] 1860-1990	1990	**Potential by 2020–2025**[c]	**Long-Term Technical Potentials**[d]	**Annual Flows**
Hydro	560	21	35–55	>130	>400
Geothermal	–	<1	4	>20	>800
Wind	–	–	7–10	>130	>200000
Ocean	–	–	2	>20	>300
Solar	–	–	16–22	>2600	>3000000
Biomass	1150	55	72–137	>1300	
Total	1710	76	130–230	>4200	>3000000

Sources: Hall *et al.*, 1993; Moreira and Poole, 1993; Grubb and Meyer, 1993; Johansson *et al.*, 1993; Swisher and Wilson, 1993; WEC, 1993b, 1994; Dessus *et al.*, 1992; Grübler and Nakicenovic, 1992; Hall, 1991; IPCC, 1992; Jensen and Sørensen, 1984; Sørensen, 1979.

Notes: All totals have been rounded; – = negligible amounts; blanks = data not available.

[a] All estimates have been converted into thermal equivalent with an average factor of 38.5%.

[b] Grübler and Nakicenovic, 1992.

[c] Range estimated from the literature. Survey includes the following sources: Johansson *et al.*, 1993; WEC, 1993b; Dessus *et al.*, 1992; EPA, 1990. It represents renewable potentials by 2020–2025, in scenarios with assumed policies for enhanced exploitation of renewable potentials.

[d] Long-term technical potentials are based on the Working Group II evaluation of the literature sources given in this table. This evaluation is intended to correspond to the concept of fossil energy resources, conventional and unconventional.

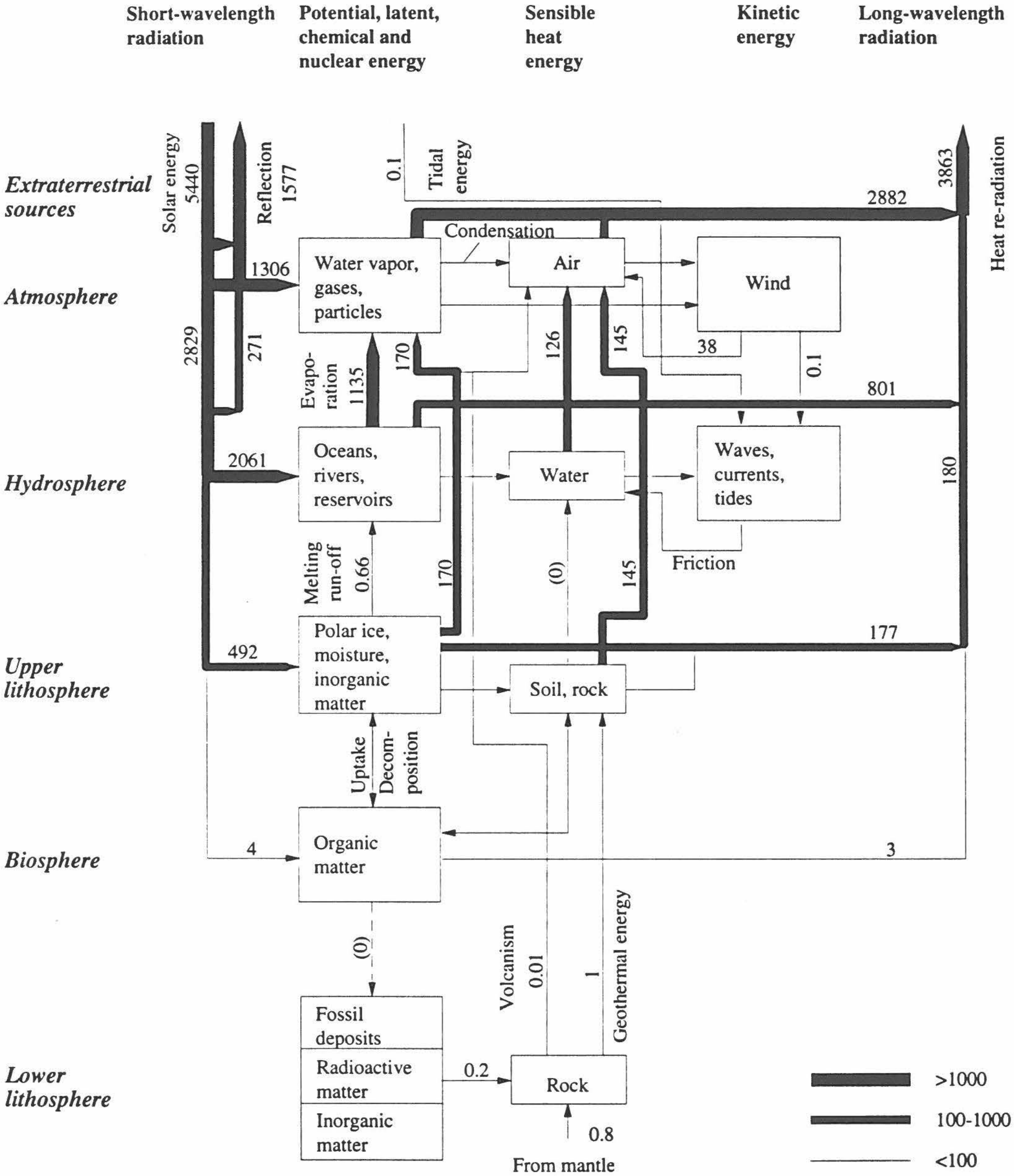

Figure B-10: Global energy balance and flows without anthropogenic interference. The energy flows are in units of 1,000 EJ/yr. Numbers in parentheses are uncertain or rounded. Source: Sørensen, 1979.

Hydropower is currently the most-developed modern renewable energy source worldwide. Table B-4 shows that the maximum technical potential is almost as large as the total final electricity consumption in 1990 as given in Table B-2 (WEC, 1993b; Moreira and Poole, 1993).

The technology to harness geothermal resources is established. Its current total use is about 0.2 EJ of electricity (Arai, 1993; Häfele *et al.*, 1981). There are four types of geothermal occurrences: hydrothermal sources, hot dry rock, magma, and geopressurized sources. The total accessible resource base of geothermal energy to a depth of 5 km is more than 126 million EJ (Palmerini, 1993), but occurrences within easily accessible layers of the crust reduce the technical potential. The annual flow from Earth is estimated at about 800 EJ/yr (Sørensen, 1979). The long-term technical potential could be greater than 20 EJ—especially if deep drilling costs can be reduced, as these are a major limitation to this energy source.

The energy flux of the atmosphere corresponds to about 200,000 EJ/yr of wind energy. The height limitations of wind converters, the distance of offshore sites, and insufficient wind velocities and land use all limit the practical potential. The ultimate potential of wind-generated electricity worldwide could indeed be very large: Some estimates place it at 50 times current global final electricity consumption (Grubb and Meyer, 1993; WEC, 1993b; Cavallo *et al.*, 1993; Gipe, 1991; Häfele *et al.*, 1981). Wind electricity is produced at many sites, and it is often also an economic option for electricity generation. The conversion efficiency is not the real barrier to the successful operation of wind-powered electricity generators. The technological challenge is that wind velocity is not constant in magnitude and direction. To utilize much higher windspeeds offshore, one option is to install floating windmills and to transport the electricity generated directly to the location of consumption or to use it for on-board hydrogen production.

Ocean energy flows include thermal energy, waves, tides, and the sea-freshwater interfaces as rivers flow into oceans. The low temperature gradients and low wave heights lead to an annual flow up to 300 EJ/yr of electricity. The technical potential is about 10 to 100 times smaller (Cavanagh *et al.*, 1993; WEC, 1993b; Baker, 1991; Sørensen, 1979).

All conceivable human energy needs could be provided for by diverting only a small fraction of the solar influx to energy use, assuming that a significantly large area could be devoted to solar energy gathering because of low spatial energy densities. Solar thermal and photovoltaic demonstration power plants are operating in a number of countries. Many gigawatts (GW) of installed electric capacity could be constructed after a few years of development. The main challenge is to reduce capital costs. Other proposals also have been made—for instance, placing solar power satellites in space.

Four general categories of biomass energy resources are used for fuels: fuelwood, wastes, forests, and energy plantations. Biomass wastes originate from farm crops, animals, forestry wastes, wood-processing byproducts, and municipal waste and sewage. The potential of biomass energy crops and plantations depends on the land area available, the harvestable yield, its energy content, and the conversion efficiency. Biomass potentials by 2020–2025 in Table B-4 are based on a literature survey of estimates and scenarios (Johansson *et al.*, 1993; WEC, 1993b; Hall, 1991). The technical potential of biomass energy crops and plantations is especially difficult to estimate. Based on land-use capacity studies, estimates of the land available for tropical plantations range between 580 and 620 million ha (Houghton *et al.*, 1991; Grainger, 1990).

B.4. Energy-Related Chapters

A number of chapters in this report are devoted to the assessment of energy-related impacts of and adaptation to climate change and to energy-related mitigation options. Vulnerability to climate change (including impacts and adaptation) concerning the energy, industry, and transportation sectors is considered in Chapter 11; human settlements are covered in Chapter 12. The general conclusion is that the sensitivity of the energy, industry, and transportation sectors is relatively low, whereas the capacity for autonomous adaptation is expected to be high if climate change is relatively gradual and not too drastic. Infrastructure and activities in these sectors would be susceptible to sudden changes and surprises; however, the subsectors most sensitive to climate change include agroindustry, renewable energy production including hydroelectric generation, construction, and manufacturing heavily dependent on water supplies. The most vulnerable human settlements are located in damage-prone areas of the developing world that do not have resources to cope with impacts.

Energy-related options for controlling the sources and enhancing the sinks of GHGs have an important role, to a varying degree, in all of the mitigation chapters. Chapter 19 assesses energy supply mitigation options, and the following three chapters, 20 through 22, consider individual sectors—industry, transportation, and human settlements, respectively. In addition, mitigation options related to energy supply and use (e.g., biomass) are considered in Chapters 23 and 24 on agriculture and forestry, respectively.

Energy-related emissions account for the largest share of CO_2 sources and have varying importance in the emissions of other GHGs. Global primary energy needs are expected to increase anywhere between 540 and 2,500 EJ by 2100, according to the IS92 IPCC scenarios. A detailed assessment and evaluation of IPCC and other energy and emissions scenarios is provided in *An Evaluation of the IPCC IS92 Emission Scenarios* (Alcamo *et al.*, 1995). With increases in global primary energy, GHG emissions will continue to grow unless they are mitigated. The general conclusion in Chapters 19 to 24 is that the technological potential to achieve significant emission reductions is indeed large, but there are important uncertainties regarding the ease, timing, and cost of implementing mitigation options and measures.

Implementation depends on successful research and development, the existence of the right market and institutional conditions, and timely market penetration, as well as the adoption of new technologies and practices by firms and individuals. Government policies are an important element in the creation of appropriate market conditions and incentive structures.

Chapter 25, the last of the mitigation options chapters, evaluates strategies that emphasize land use and highlights some key cross-cutting themes related to implementation and energy supply and use. It concludes with a discussion of nontraditional mitigation options such as "geoengineering," which might be involved as "last resort options" for the future.

The last two chapters of the report, Chapters 27 and 28, describe methods for assessing mitigation options and offer an inventory of mitigation technologies, respectively. These methods can be used to develop mitigation strategies and evaluate mitigation projects and, together with the inventory, are available to all countries.

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