part II

energy resources and technology options

CHAPTER 5

energy resources

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ABSTRACT

A comprehensive account of the world's energy resource endowment is essential for any long-term energy assessment. Energy resources exist in different forms—some exist as stocks and so are exhaustible, others exist as flows and are inexhaustible, and a third form is based on exhaustible stocks that can be leveraged to resemble renewables. Most important, energy resources evolve dynamically as a function of human engineering ingenuity, driven by the desire to supply affordable and convenient energy services. Although the term stocks suggests finiteness (which is ultimately correct), the accessible portion depends on technology and on the future demand for that resource. Resources not demanded by the market are 'neutral stuff'. Demand plus advances in technology and knowledge turn neutral stuff into reserves that are replenished upon use by further advances in technology and knowledge, enabling humans to tap into resources previously beyond reach. But for stocks there will eventually be a limit. In contrast, resources based on annually recurring flows are distinctly different from stocks: harvested prudently, they are renewable. But resources are not an end in themselves, and their attractiveness must be seen in the context of societies' energy service needs, of the technologies that convert resources into energy services, and of the economics associated with their use. This chapter assesses whether long-term energy resource availability could impede sustainable development and, based on a dynamic technology concept, provides a comprehensive account of the world's energy resource endowment. ■

> Hydrocarbon occurrences become resources only if there is demand for them and appropriate technology has been developed for their conversion and use.

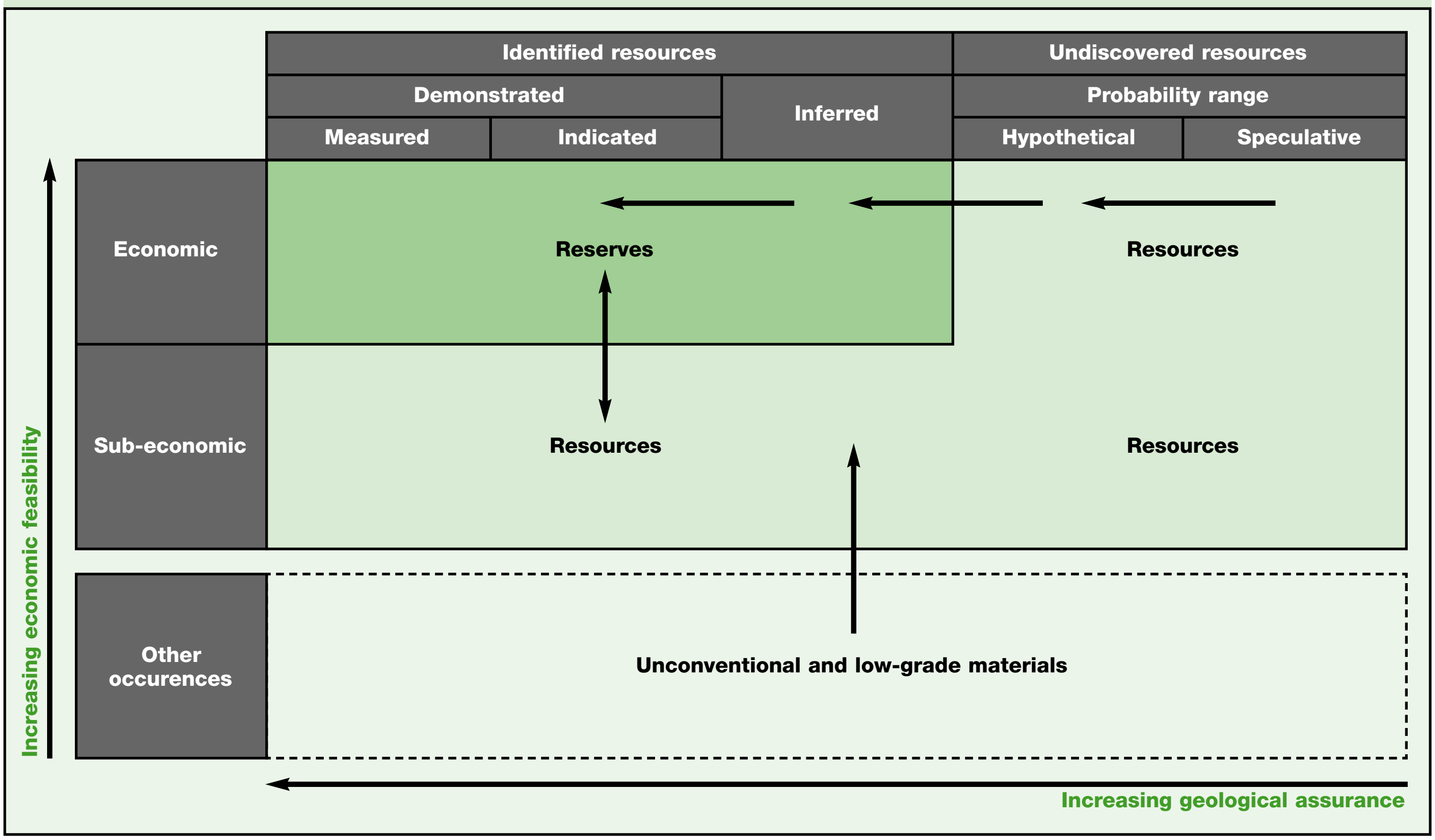
This chapter reviews fossil, nuclear, and renewable energy resources. The reserve and resource volumes presented here cover the ranges considered robust by most of the lead authors. The main controversy yet to be resolved concerns the different views on the roles of technology and demand in the long-term availability of a particular resource. Subject to debate is the extent to which reserves can be converted from additional conventional resources with lower geological assurance and from unconventional resources lacking economic attractiveness given current markets and technologies. Natural flows are immense for renewable resources, but the level of their future use will depend on the technological and economic performance of technologies feeding on these flows as well as on possible constraints on their use. The long-term availability of energy resources will likely become more an issue of the degree to which future societies want to balance environmental and economic tradeoffs, control greenhouse gas emissions, and internalise externalities, or of the technological and economic performance of different clean energy conversion technologies, than a question of resource existence.

This chapter examines long-term energy resource availability primarily from the perspectives of theoretical maximums, or ultimately recoverable resources. Admittedly, it can be argued that an analysis based on ultimately recoverable resources is irrelevant—hydrocarbon occurrences or natural flows become resources only if there is demand for them and appropriate technology has been developed for their conversion and use. Indeed, energy resources generally should not be scrutinised without reference to the chain extending from the extraction of resources to the supply of energy services—that is, along all the conversion steps to the point of what consumers really want: transportation, communication, air conditioning, and so on. But the assessment in this volume has been structured so that each link of the chain is explored separately. Energy conversion technologies are discussed in chapters 7 (renewable energy technologies) and 8 (advanced fossil and nuclear energy technologies), as well as in chapter 6 (energy efficiency).

Definitions and units

A variety of terms are used to describe energy reserves, and different authors and institutions have different meanings for the same terms. Meanings also vary for different energy sources. The World Energy

FIGURE 5.1. PRINCIPLES OF RESOURCE CLASSIFICATION



Source: Based on McKelvey, 1967.

Technological improvements are continuously pushing resources into the reserve category by advancing knowledge and lowering extraction costs.

Council defines resources as "the occurrences of material in recognisable form" (WEC, 1998). For oil, it is essentially the amount of oil in the ground. Reserves represent a portion of resources and is the term used by the extraction industry. British Petroleum notes that proven reserves of oil are "generally taken to be those quantities that geological and engineering information indicates with reasonable certainty can be recovered in the future from known reservoirs under existing economic and operating conditions" (BP, 1999). Other common terms include probable reserves, indicated reserves, and inferred reserves—that is, hydrocarbon occurrences that do not meet the criteria of proven reserves. Undiscovered resources are what remains and, by definition, one can only speculate on their existence. Ultimately recoverable resources are the sum of identified reserves and the possibly recoverable fraction of undiscovered resources and generally also include production to date. Then there is the difference between conventional and unconventional occurrences (oil shale, tar sands, coalbed methane, clathrates, uranium in black shale or dissolved in sea water), especially the rate at which unconventional resources can be converted into conventional reserves.

To the extent possible, this chapter uses the McKelvey box, which presents resource categories in a matrix with increasing degrees of geological assurance and economic feasibility (figure 5.1). This scheme, developed by the U.S. Bureau of Mines and the U.S. Geological Survey (USGS, 1980), is to some extent also reflected in the international classification system recently proposed by the United Nations.

In this classification system, resources are defined as concentrations of naturally occurring solid, liquid, or gaseous material in or on the Earth's crust in such form that economic extraction is potentially feasible. The geologic dimension is divided into identified and undiscovered resources. Identified resources are deposits that have known location, grade, quality, and quantity or that can be estimated from geologic evidence. Identified resources are further subdivided into demonstrated (measured plus indicated) and inferred resources, to reflect varying degrees of geological assurance. Reserves are identified resources that are economically recoverable at the time of assessment (see the British Petroleum definition, above).

Undiscovered resources are quantities expected or postulated to exist under analogous geologic conditions. Other occurrences are materials that are too low-grade or for other reasons not considered technically or economically extractable. For the most part, unconventional resources are included in 'other occurrences'.

The boundary between reserves, resources, and occurrences is current or expected profitability of exploitation, governed by the ratio of market price to cost of production. Production costs of reserves are usually supported by actual production experience and feasibility analyses, while cost estimates for resources are often inferred from current production experience adjusted for specific geological and geographic conditions.

For several reasons, reserve and resource quantities and related supply-cost curves are subject to continuous revision. Production inevitably depletes reserves and eventually exhausts deposits, while successful exploration and prospecting add new reserves and resources. Price increases and cost reductions expand reserves by moving resources into the reserve category and vice versa. The dynamic nature of the reserve-resource relationship is illustrated by the arrows in figure 5.1. Technology is the most important force in this process. Technological improvements are continuously pushing resources into the reserve category by advancing knowledge and lowering extraction costs.

The outer boundary of resources and the interface to other occurrences is less clearly defined and often subject to a much wider margin of interpretation and judgement. Other occurrences are not considered to have economic potential at the time of classification. But over the very long term, technological progress may upgrade significant portions to resources.

In 1992 the United Nations Economic Commission on Europe (UNECE) launched an effort to define a generally applicable resource classification scheme with a higher resolution of technical and economic feasibility than the McKelvey box. By adding a third dimension—the level of actual feasibility of extraction based on geological engineering assessments—this new classification provides a more accurate picture of the accessibility of resources. In 1997 the United Nations International Framework Classification for Reserves/Resources—Solid Fuels and Mineral Commodities (UNFC) was completed and recommended by the Economic and Social Council (ECOSOC) for world-wide application. But it will take time for the UNFC to be universally adopted by public and private institutions and for fossil reserves and resources to be consistently reported in compliance with the UNFC.

For renewable energy sources, the concepts of reserves, resources, and occurrences need to be modified. Renewables represent annual flows available, in principle, on an indefinite sustainable basis. Fossil energy reserves and resources, although expanding over time, are fundamentally finite quantities. In this context the annual natural flows of solar, wind, hydro, and geothermal energy and quantities grown by nature in the form of biomass (often referred to as theoretical potentials) would correspond to occurrences. The concept of technical potentials can be used as a proxy for energy resources, while economic potentials correspond to reserves. The distinction between theoretical and technical potentials reflects the degree of use determined by thermodynamic or technological limitations without consideration of practical feasibility or costs. Thus the economic potential is the portion of the technical potential that could be used cost-effectively. In terms of reserves, resources, and occurrences of hydrocarbons, economic and technical potentials are dynamically moving targets in response to market conditions and technology availability and performance.

This chapter reports oil resources in gigatonnes (1 Gt = 10^9 tonnes) and exajoules (1 EJ = 10^{18} joules) using the energy equivalent of 42 gigajoules per tonne of oil equivalent (GJ per toe). Gas resources are reported in tera cubic metres (1 Tm^3 = 10^{12} cubic metres) and converted to EJ using 37 gigajoules per 1,000 cubic metres (GJ per 1,000 m^3). Coal resources are usually reported in natural units, although the energy content of coal may vary considerably within and between different coal categories. The Bundesanstalt für Geowissenschaften und Rohstoffe (Federal Institute for Geosciences and Natural Resources, referred to here as the BGR) in Hannover (Germany) is the only institution that converts regional coal occurrences into tonnes of coal equivalent (1 tce = 29 gigajoules). Thus coal resource data come from the BGR. Uranium and other nuclear materials are usually reported in tonnes of metal. The thermal energy equivalent of 1 tonne of uranium in average once-through fuel cycles is about 589 terajoules (IPCC, 1996a).

Oil reserves and resources

Views on the long-term availability of oil and natural gas continue to spark controversy and debate. One school of thought believes that the best oil fields have already been discovered and that the amount of oil still to be discovered is somewhat limited. The other school regards oil reserves as a dynamic quantity, driven by demand and technological advances. The second school is more optimistic about future hydrocarbon availability.

Ultimately recoverable resources—the static or geologists' view

For many years, world oil reserves have experienced small but steady increases, which implies that the discovery or delineation of new reserves has at least kept pace with production. But many geologists focus on the concept of a quasi-fixed stock of hydrocarbon occurrences that, once production commences, can only decrease. For oil, they argue that few new oil fields have been discovered since the mid-1970s, and that most reserve increases have come from revisions of previously underestimated existing reserves (Hatfield, 1997; Campbell and Laherrere, 1998) and improved recovery techniques. Peak production lags behind peak discovery (of the mid-1960s) by several decades. Larger and more obvious fields are found first, leading to an early peak in discovery and diminishing returns in

TABLE 5.1. ESTIMATED OIL RESERVES

Region	Identified reserves (Masters and others, 1994)		Identified reserves plus 95%[a] (Masters and others, 1994)		Identified reserves plus mode[b] (Masters and others, 1994)		Identified reserves plus 5%[c] (Masters and others, 1994)		Proven recoverable reserves (WEC, 1998)		Proven reserves (BP, 1999)		Total resources from enhanced oil recovery[d]	
	Gigatonnes	Exajoules	Gigatonnes	Exajoules	Gigatonnes	Exajoules	Gigatonnes	Exajoules	Gigatonnes	Exajoules	Gigatonnes	Exajoules	Gigatonnes	Exajoules
North America	8.5	356	14.3	599	17.0	712	23.7	992	4.6	193	4.6	193	13.6	569
Latin America and Caribbean	17.3	724	22.6	946	26.2	1,097	41.6	1,742	19.2	804	19.9	833	23.8	996
Western Europe	5.6	234	6.8	285	7.7	322	11.2	469	2.5	105	2.5	105	3.9	163
Central and Eastern Europe	0.3	13	0.4	17	0.5	21	1.1	46	0.3	13	0.2	8	0.5	21
Former Soviet Union	17.0	712	25.1	1,051	30.6	1,281	49.9	2,089	8.0	335	9.1	381	11.2	469
Middle East and North Africa	87.6	3,668	97.0	4,061	104.6	4,379	126.4	5,292	99.6	4,170	96.8	4,053	59.2	2,479
Sub-Saharan Africa	4.0	167	5.9	247	7.3	306	12.3	515	4.0	167	4.5	188	3.3	138
Pacific Asia	3.1	130	4.1	172	4.8	201	7.3	306	1.5	63	1.5	63	2.1	88
South Asia	1.0	42	1.1	46	1.3	54	1.8	75	0.8	33	0.5	21	0.6	25
Centrally planned Asia	5.1	214	7.8	327	9.8	410	17.9	749	5.4	226	3.4	142	3.7	155
Pacific OECD	0.4	17	0.6	25	0.7	29	1.3	54	0.4	17	0.4	17	0.5	21
Total[e]	**150**	**6,277**	**186**	**7,776**	**210**	**8,812**	**295**	**12,329**	**146**	**6,126**	**143**	**6,004**	**123**	**5,124**

Note: Excludes cumulative production to the date of assessment.
a. Identified reserves plus estimates of undiscovered resources with a 95 percent probability of discovery. b. Identified reserves plus estimates of undiscovered resources with a 50 percent probability of discovery. c. Identified reserves plus estimates of undiscovered resources with a 5 percent probability of discovery. d. Includes enhanced recovery of past and future oil production. e. Totals rounded.

exploration: the more that is found, the less is left to find. Fields that are smaller and harder to find and to exploit follow, but eventually the fixed stock will be exhausted. Some 90 percent of current global oil production comes from fields more than 20 years old.

Cumulative production is a good proxy for geological knowledge gained through exploration experience. All these facts leave no room for any conclusion other than that peak production is being approached rapidly. In the 1960s ultimately recoverable resources became a popular concept for quantifying the fixed stock of hydrocarbon occurrences. Ultimately recoverable resources include cumulative production, proven reserves at the time of estimation, and oil remaining to be discovered—in other words, the ultimate oil wealth available to humans. For the past 40 years most estimates of ultimately recoverable resources for conventional oil have ranged from 200–400 gigatonnes. More recently, Campbell and Laherrere (1998) put ultimately recoverable reserves at about 250 gigatonnes, Hiller (1999) at 350 gigatonnes, Edwards (1997) at 385 gigatonnes, Masters and others (1994) at 281–390 gigatonnes, and Odell (1997) at 410 gigatonnes. All these estimates include production to the date of estimation (96–110 gigatonnes).

The debate on the size of ultimately recoverable resources and the time horizon when the depletion midpoint will be reached includes only conventional oil occurrences. Shale oil, tar sands (natural bitumen), and heavy crude oil are considered unconventional oil resources, defined as occurrences that cannot be tapped with conventional production methods for technical or economic reasons or both (Rogner, 1997; Gregory and Rogner, 1998). These resources form a large part of the vast store of hydrocarbons in the Earth's crust and, in the case of oil, have been assessed to be at least as large as conventional oil resources (see below). The existence of unconventional oil and gas is acknowledged by 'fixed stock' analysts, but they are less sanguine about the future technological potential for bringing these resources to market. Technological pessimism and an exclusive focus on conventional oil largely explain the geologists' view that global oil production will reach its peak and mid-depletion point in the near future.

Conventional oil. Table 5.1 reports recent estimates, excluding cumulative production to date, of identified or proven oil reserves and natural gas liquids. All these estimates report reserves at around 1,000 billion barrels of oil (143–150 gigatonnes).

Masters and others (1994) estimate identified reserves on 1 January 1993 to be 150 gigatonnes (6,277 exajoules), only slightly higher than British Petroleum and World Energy Council estimates of proven reserves at the end of 1997.[1] Masters and others also estimate undiscovered oil resources based on a modified Delphi technique

TABLE 5.2. ESTIMATED UNCONVENTIONAL OIL RESERVES AND

Region	Oil shale						Heavy crude oil					
	Identified resources (BGR, 1998)		Total resources (BGR, 1998)		Proven recoverable and estimated additional reserves (WEC, 1998)		Oil in place (BGR, 1998)		Reserves and resources (BGR, 1998)		Future potential recovery (Meyer, 1997)	
	Gigatonnes	Exajoules	Gigatonnes	Exajoules	Gigatonnes	Exajoules	Gigatonnes	Exajoules	Gigatonnes	Exajoules	Gigatonnes	Exajoules
North America	1.1	48	351.6	14,767	217.0	9,114	15.7	659	2.3	96	2.0	82
Latin America and Caribbean	0.3	14	19.4	814	9.6	405	229.3	9,631	59.7	2,509	51.2	2,152
Western Europe	0.5	22	8.9	374	0.0	1	9.8	412	3.7	155	3.2	133
Central and Eastern Europe	1.1	45	2.8	116	0.0	0	0.1	4	0.1	5	0.1	5
Former Soviet Union	4.2	178	9.6	405	6.5	273	0.1	4	19.2	805	16.4	690
Middle East and North Africa	7.6	319	8.1	340	28.0	1,175	45.2	1,898	20.2	847	17.3	726
Sub-Saharan Africa	0.0	0	16.4	690	0.0	0	1.4	59	0.9	39	0.6	27
Pacific Asia	1.0	40	1.0	40	1.7	71	1.1	46	1.5	62	1.4	59
South Asia	0.0	0	0.0	0	0.0	0	1.0	42	0.0	2	0.0	1
Centrally planned Asia	0.6	25	20.0	840	0.0	0	10.8	454	2.6	111	2.3	95
Pacific OECD	3.8	160	44.5	1,870	36.0	1,513	0.0	0	0.0	1	0.0	1
Total	**20.3**	**851**	**482.3**	**20,256**	**298.9**	**12,552**	**314.5**	**13,209**	**110.3**	**4,632**	**94.5**	**3,971**

and geological analogies. Their low estimate (95 percent probability of discovery) brings their total for recoverable conventional oil reserves to 186 gigatonnes (7,771 exajoules). If cumulative production until 1994 of 95 gigatonnes (3,990 exajoules) is added, the total for ultimately recoverable resources is 281 gigatonnes (11,800 exajoules). The medium (mode) estimate of undiscovered resources brings total recoverable oil reserves to 210 gigatonnes (8,812 exajoules) and ultimately recoverable resources to 305 gigatonnes (12,810 exajoules). The high (5 percent probability) estimate of undiscovered resources brings total recoverable oil reserves to 295 gigatonnes (12,329 exajoules) and ultimately recoverable resources to 390 gigatonnes (16,380 exajoules).

In its 1998 survey the World Energy Council reported proven recoverable oil reserves of 146 gigatonnes (6,126 exajoules) and estimates additional recoverable reserves (excluding speculative occurrences) of 28 gigatonnes (1,192 exajoules), for a total of 174 gigatonnes (7,318 exajoules). This compares well with the Masters and others estimate of identified reserves plus 95 percent probability of undiscovered resources of 186 gigatonnes. The oil reserve estimates in table 5.1 reflect the views of geologists on the availability of conventional oil and are consistent with the ultimately recoverable resource estimates presented earlier.

RESOURCES

Tar sands (natural bitumen)					
Oil in place (BGR, 1998)		Reserves and resources (BGR, 1998)		Proven recoverable and estimated additional reserves (WEC, 1998)	
Gigatonnes	Exajoules	Gigatonnes	Exajoules	Gigatonnes	Exajoules
233	9,786	40.7	1,710	51.7	2,173
190	7,980	33.2	1,395	1.2	49
0	0	0.0	0	0.0	0
0	0	0.0	0	0.0	0
232	9,744	40.5	1,703	0.0	0
0	0	0.0	0	0.0	0
3	126	0.5	22	0.0	0
0	0	0.0	0	0.0	0
0	0	0.0	0	0.0	0
0	0	0.0	0	0.0	0
0	0	0.0	0	0.0	0
658	**27,636**	**115.0**	**4,830**	**52.9**	**2,222**

Today only about 35 percent of the oil in place is recovered by primary and secondary production methods. With enhanced oil recovery methods, this rate can be increased to as much as 65 percent of the original oil in place in a reservoir, though at higher extraction costs (BGR, 1995). Thus the application of enhanced oil recovery methods in abandoned fields and new developments increases conventional oil resources.

Table 5.1 shows the potential resources resulting from the use of enhanced oil recovery techniques. Resources are calculated based on an average recovery rate of 35 percent achieved in historical production and used in the delineation of proven recoverable reserves, and an enhanced oil recovery rate of 15 percent, for an overall recovery rate of 50 percent.

Unconventional oil. The vast amounts of unconventional oil occurrences include oil shale, heavy crude oil, and tar sands. Unconventional oil is already economic to exploit in some places, so some is defined as reserves. Further development may depend on higher oil prices, technological developments, and long-term demand for liquid fuels. According to BGR (1998), reserves of unconventional oil could be as high as 245 gigatonnes, substantially exceeding proven reserves of conventional oil (table 5.2).

Oil shale is a sedimentary rock rich in organic matter containing more than 10 percent kerogen. It can be used directly as a fuel in power plants or processed to produce synthetic petroleum products. The kerogen content of oil shale varies widely. According to BGR (1995), only about 1 percent of world resources contains more than 100 litres of oil per cubic metre rock, while 85 percent have less than 40 litres per cubic metre.

Data on oil shale resources are presented in table 5.2. The most recent BGR (1998) estimate of oil shale resources is 482 gigatonnes, down from 920 gigatonnes in the 1995 estimate. WEC (1998) estimates recoverable and estimated additional reserves at 299 gigatonnes. Major oil shale resources are in China, Estonia, the United States, Australia, and Jordan. The large regional differences between the BGR and WEC estimates are likely the result of different definitions.

Because of the high costs of mining and processing, oil shale is produced only in small quantities in China and Estonia. Estonia is the only country with an economy dominated by oil shale as a source of energy and for more than 70 years has been the largest user of oil shale in power generation. Recent production totalled 20 million tonnes of oil shale a year (Hobbs, 1995).

Heavy crude oil is defined as high-viscosity crude oil with a density equal to or less than 20° API (934 kilograms per cubic metre). Extra heavy oil is crude oil with a density equal to or less than 10° API (1,000 kilograms per cubic metre). Unlike tar sands, the viscosity of these hydrocarbons is below 10,000 millipoise (see below). Heavy oil is formed by the degradation of conventional oil in shallow reservoirs.

Recent estimates of heavy oil resources are summarised in table 5.2. BGR (1995) estimates oil in place to be 315 gigatonnes. In BGR (1998), 33 of these are considered reserves and 77 are considered resources, for a total of 110 gigatonnes—well within the range of future potential recovery given by Meyer (1997). About half of heavy oil resources are in Venezuela; the former Soviet Union, Kuwait, Iraq, Mexico, and China account for most of the rest.

Meyer (1997) uses the term *unproved reserves* because his estimates include some probable and possible reserves. Quantities stated under undiscovered potential recovery include all resources based on geological and engineering judgement, using a recovery factor of 10 percent.

Some 8 percent of world oil production come from heavy oil reservoirs, with Venezuela, the United States, Canada, Iraq, Mexico, and the former Soviet Union being major producers (BGR, 1998). Due to the nature of heavy oil, enhanced oil recovery methods such as steam flooding and hot water, polymer, and carbon dioxide injection are generally required for its extraction.

Tar sands (natural bitumen) and extra heavy oil are sands or sandstones that contain a large portion of tarry hydrocarbons with a viscosity exceeding 10,000 millipoise. They are formed by thermal metamorphism and biodegradation of conventional oil deposits. The high viscosity of these hydrocarbons requires unconventional extraction methods such as mining with bucket-wheel excavators or in truck and shovel operations. Natural bitumen typically contains large portions of sulphur and trace elements, including vanadium and nickel.

BGR (1998) estimates that 115 of the 658 gigatonnes of tar sands qualify as possible reserves (see table 5.2). Commercial production is limited to the Athabasca tar sand deposits of Alberta (Canada), with a volume of 25 million tonnes in 1998 (WEC, 1998). To reduce the environmental disturbance caused by surface mining, in situ techniques are increasingly used (box 5.1). In addition, new extraction technologies, such as steam-assisted gravity drainage, are being developed to reduce oil viscosity through steam injection (George, 1998). The use of extra heavy oil has commenced in the Orinoco oil belt of Venezuela (BGR, 1998).

Available resources—the dynamic or economists' view

Unlike geologists, who tend to treat resources as an innate component of the physical world, economists view what exists in the Earth's crust as 'neutral stuff' (Odell, 1998) that becomes a resource only if

BOX 5.1. ENVIRONMENTAL OBSTACLES TO EXTRACTING UNCONVENTIONAL OIL

The production of unconventional oil and the necessary upgrade to marketable fuels can hurt local environments. Mining, conversion, and upgrading to synthetic crude oil can produce toxic heavy metals and large quantities of solid and acidic liquid and gaseous wastes that need to be contained, cleaned, and disposed of in an environmentally benign manner. This may require stringent environmental controls and new policies for toxic waste disposal. Extracting hydrocarbons from unconventional oils such as tar sands, heavy oils, and oil shale involves very large surface (open-pit or strip) mining and underground mining (room and pillar technique), steam soaking, steam flooding, or in situ combustion. Here the production of tar sand and its upgrading to synthetic crude oil are used to show the potential environmental constraints of large-scale unconventional oil production.

The production of synthetic crude oil from Alberta, Canada's tar sand deposits involves open-pit mining and handling of 5 tonnes of tar sands and overburden per barrel of oil produced (Penner and others, 1982), milling to separate the bitumen from the sand, and upgrading it to commercial quality. Syncrude, a Canadian company, processes 510,000 tonnes of tar sands a day and recovers about one barrel of heavy oil for every 2 tonnes of tar sands processed (Stosur and others, 1998). A hot water process is the most common for extracting oil from the sand. The process is energy-intensive and requires large quantities of hot water. Syncrude operations require 1,400 tonnes an hour of water heated to nearly 500 degrees Celsius. Water is recycled to the maximum extent (90 percent). The remaining materials (tailings) after the bitumen has been extracted (extraction rate some 90 percent) are liquids and sand. Most of the tailings are the excavated overburden rock and rejected sand; both can be stockpiled and used as backfill with little threat to the environment (Stosur and others, 1998).

Things are different for the liquid tailings, which are contaminated with organic and inorganic compounds (sulphur, porphyrins, salts of organic acids) and can seriously damage nearby aquatic ecosystems. The liquid is stored in settling ponds, allowing water to clarify before it is recycled. These ponds are designed as 'zero discharge' basins, and no process-affected water is discharged in running waters. But while tailings sand settles out quickly, the fine-grained materials (silts and clays) and residual bitumen consolidate slowly and can pose a long-term problem and liability. Tailings ponds must be constructed to last several decades and must be guarded against erosion, breaching, and foundation creep until better disposal practices become available (Stosur and others, 1998). New processes such as dry retorting—which generates dry tailings—are expected to minimise the risk of acid drainage from tar sand tailings. Other methods include faster consolidation of fine tailings, detoxification of tailing pond water, and reprocessing of fine tailings (including co-production of minerals and metals).

Spent tar sand (mainly sand, silt, and clay contaminated with the remaining bitumen and caustic compounds) is put in specially designed storage areas to avoid acid drainage or used as fill material in mine reclamation efforts. While the disrupted land area can be considerable, land reclamation is usually imposed on mine operators to limit permanent environmental damage and to return land to a stable, biologically self-sustaining state.

Upgrading operations are the primary source of airborne emissions. Sulphur dioxide, particulates, hydrocarbons, vanadium, and nickel were originally of major concern. In addition, bitumen contains several carcinogenic polycyclic aromatic hydrocarbons (WHO, 1982). Hydrotreaters remove sulphur and nitrogen and produce elemental sulphur as a by-product. Nitrogen is removed as ammonia and used as an under-boiler fuel or for chemical feedstock. Hydrogen sulphide is removed from the by-product fuel gas that fuels parts of the upgrading operations. The synthetic crude oil produced from Alberta's tar sand deposits is 32–33º API with 0.1–0.2 percent sulphur. It contains no residue, while typical conventional crudes have about 8 percent residue.

Stosur and others (1998) estimate that only 15 percent of tar sand resources are suitable for surface mining. The rest would have to be extracted by in situ methods, which minimise land disturbance through multiwell pads and horizontal drilling (Sadler and Houlihan, 1998). To reduce odour and greenhouse gas emissions, care must be taken to collect and reuse or flare the gases generated by the process.

Alberta's tar sand operations indicate that environmental protection is the result of effective environmental regulation and controls, including a balance of resource development and resource conservation and of environmental and socioeconomic policies.

The oil industry has historically responded to demand by finding and developing reserves, even given the long lead time for this process.

there is a market demand for it. Put differently, "there are huge amounts of hydrocarbons in the earth's crustæ (Adelman and Lynch, 1997), and "estimates of declining reserves and production are incurably wrong because they treat as a quantity what is really a dynamic process driven by growing knowledge" (Nehring, 1998). Improvements in technology—such as three-dimensional seismic surveys and extended-reach drilling—have allowed higher recovery rates from existing reservoirs and the profitable development of fields once considered uneconomic or technically beyond reach, expanding the boundary of reserves and shifting resources into the reserve category.

In addition, economists argue, a distinction between conventional and unconventional occurrences is irrelevant. Today most unconventional occurrences are neutral stuff and will become resources and reserves if there is sufficient demand. In fact, certain unconventional occurrences—heavy oil, tar sands, coalbed methane and gas from aquifers—have already started to 'come in from the margin'. Conventional discoveries previously regarded as uneconomic can now be developed profitably, and recoverable reserves can be increased in fields being developed or under production. In short, economists view oil and gas reserves as a portion of the total hydrocarbon occurrences contained in the Earth's crust, where volumes depend on exploration know-how to locate and evaluate a play (delineated deposit) and on the capability of technology to extract it at an acceptable cost given sufficient demand.

The question of long-term hydrocarbon resource availability, then, is viewed from the perspective of anticipated demand in competitive markets—taking into account technological change and growing knowledge. In the presence of sufficiently large conventional oil reserves there is, at present, no demand for the large-scale use of abundant unconventional oil occurrences (see above). This explains the absence of any significant motivation for a comprehensive and systematic evaluation of these resources or for the development of technology for their economic and environmentally acceptable recovery.

Economists take proven conventional oil reserves of 150 gigatonnes as a point of departure that, based on their definition, can be brought to the market at post-1986 price levels. In addition, economists point to industry expectations that proven reserves will grow 50–70 gigatonnes by 2020 (Shell, 1996). They point out that the oil industry has historically responded to demand by finding and developing reserves, even given the long lead time for this process: since World War II it has taken more than 40 years to move from identifying reserves to producing resources. This is seen as a clear indication that the process of stock replenishment is working effectively.

A bigger role for unconventional oil. Economists also argue that unconventional oil should be viewed as an important element of the oil resource base—and after 2030 it will be a critical complement to conventional oil production in keeping the oil supply curve moving upwards. This long process of the changing supply pattern will be seamless from the viewpoint of oil producers. From the point of view of users the process will be unimportant, because no essential difference will arise for them merely because of the changing nature of exploitation of oil habitats in the Earth's surface. In precisely the same way, today's oil consumers do not need to consider whether their supply is from shallow or deep horizons, or from onshore or offshore locations.

The ultimate resource base of unconventional oil is irrelevant to the 21st century's energy supply. Occurrences of such oil that are already known and under exploitation can provide the global supply likely to be required in the 21st century. On the other hand, economic or environmental considerations—or both—could convert unconventional resources back to neutral stuff, as has occurred in recent decades with previously designated coal resources.

Costs and technological developments. New technologies for exploring and extracting oil have lowered exploration, development, and production costs while expanding the oil resource base. Further advances in technology must also be expected, resulting in additional reductions in cost. Part of these productivity gains will be offset by the use of more remote, harder-to-access, and smaller deposits. Still, it appears plausible that technological progress will continue to keep production costs in check.[2] The technology learning curve for synthetic crude oil production from tar sands in Alberta is a good example of the impact of technology on production costs. In 1978 a barrel of synthetic crude oil cost about $26 a barrel. By 1996 breakthroughs in the technology for producing and refining bitumen as well as better operating procedures had lowered these costs to $9.60 a barrel (Polikar and Cyr, 1998).

Two developments will likely put upward pressure on prices. The first is the increasing volume of energy that will be demanded in the first half of the 21st century. The second is the significantly increased cash flows required by the international oil industry to sustain enhanced investment in the initial large-scale exploitation of rapidly increasing volumes of unconventional oil and gas. In the 1950s the ability of consumers to secure large volumes of international oil depended on the super-normal profits that the industry was able to generate. More recent breakthroughs for gas in Europe and elsewhere were likewise achieved because of super-normal profitability in the industry. After 2030, following the introduction to global markets of large-scale unconventional hydrocarbons, prices should fall back as the long-run supply prices of the two commodities once again start to decline under conditions of advancing technology and increasing economies of scale (Odell, 1998).

Reconciling the two views

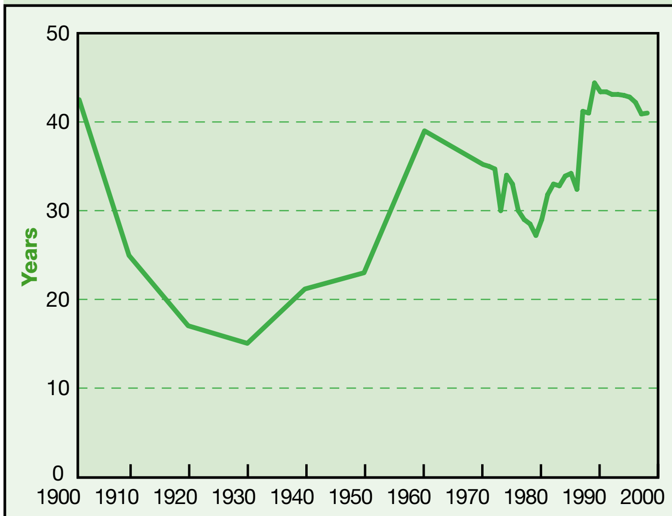
The differences between geologists' (static) and economists' (dynamic) views of oil resources can be partly explained by the way the different schools view unconventional oil. Geologists draw a strict line between conventional oil (the oil they look for) and unconventional oil (the oil that does not fit their template). Although some unconventional oil is being exploited economically, geologists take a conservative view of its long-term commercial viability. In contrast, economists consider irrelevant the dividing line between conventional and unconventional oil. They anticipate a seamless transition from one to the other as long as demand and market prices allow for a profitable return on investment. In that case, unconventional occurrences estimated to exist in the Earth's crust (see table 5.2) would extend the oil age well beyond the mid-21st century. Without demand, the issue of resource availability becomes meaningless and unconventional oil occurrences remain neutral stuff.

New technologies for exploring and extracting oil have lowered exploration, development, and production costs while expanding the oil resource base.

A historical review of the most popular guideline for the industry, the ratio of reserves to production, puts into perspective the two schools of thought. This ratio compares known reserves and current production and so measures the temporal reach of exhaustible energy reserves. These ratios typically fluctuate between 20 and 40 years.

But the notion of a reserve-to-production ratio is seriously flawed and, in the past, has led to aberrant conclusions (MacKenzie, 1996). The most erroneous conclusion is that the world will be running out of reserves by the time suggested by the ratio.[3] For oil, ratios of 20–40 years have existed since the early 20th century (figure 5.2). According to this ratio, the world should have run out of oil a long time ago. Instead, driven by economics (in essence, demand for oil), advances in geoscience, and technological progress in upstream production, reserves have been continuously replenished from previously unknown sources (new discoveries) or technologically or economically inaccessible occurrences. Although reserve additions have shifted to more difficult and potentially more costly locations, technological progress has outbalanced potentially diminishing returns.

FIGURE 5.2. RATIO OF RESERVES TO PRODUCTION FOR CONVENTIONAL CRUDE OIL, 1900–98



Source: Adapted from BP, 1998.

Gas reserves and resources

Unlike oil, gas is not subject to controversy on estimates of ultimately recoverable reserves. Proven reserves are comparable to those of oil but high relative to current and cumulative production. Still, natural gas is often viewed as the poor stepsister of oil. The development of natural gas fields requires large investments in transmission and distribution infrastructure.[4] As a result gas discoveries, especially in developing countries, are often not reported. But this does not imply a lack of gas occurrence—in fact, over the 21st century there is enormous potential for major gas discoveries.

Conventional gas

The most recent estimates of conventional gas reserves come from WEC (1998) for the end of 1996 and BP (1998) for the end of 1998. WEC gives total reserves as 177 Tm^3 (6,534 exajoules) at the end of 1996, 147 Tm^3 (5,450 exajoules) of which were proven recoverable reserves (table 5.3). The rest were additional recoverable reserves. The International Gas Union (IGU, 2000) reports total potentially recoverable reserves as high as 502 Tm^3 (18,390 exajoules).

Reserves have generally increased from survey to survey, reflecting dramatic changes in the economics of gas exploration and recovery. Reservoirs are being added in areas previously thought to have been exhausted, and new reservoirs that were previously overlooked or ignored are now being developed. Over the past 10 years reserve additions averaged 3.7 Tm^3 (134 exajoules) a year, much higher than the 1997 production of 2.2 Tm^3. Ivanhoe and Leckie (1993) note that fewer gas than oil fields are reported in developing regions, probably because gas has a lower economic and utility value, not because there are fewer gas fields.

Enhanced gas recovery using advanced recovery methods—notably hydraulic fracturing aimed at improving the permeability of reservoir rock—can substantially increase natural gas recovery in abandoned fields and newly developed reservoirs. Another, more innovative technique, horizontal air drilling, can also increase gas recovery in depleted gas zones (Elrod, 1997).

Estimates of potential reserves of natural gas resulting from enhanced gas recovery are based on a historical average gas recovery rate of 50 percent and an enhanced recovery rate of 30 percent, for a total recovery factor of 80 percent. Schollnberger (1998) uses similar assumptions in an assessment of possible reserve development through 2100. Global cumulative natural gas production through 1998 totalled 62 Tm^3 (2,276 exajoules). Applying an average recovery factor of 50 percent leads to an original amount of 124 Tm^3. Enhanced gas recovery of 30 percent then enlarges reserves by 37 Tm^3. Likewise, enhanced gas recovery reserves from future production are estimated at 106 Tm^3 using WEC (1998) total recoverable reserves of 177 Tm^3 (see table 5.3). Thus total potential natural gas reserves available from enhanced oil recovery methods are estimated at 143 Tm^3 (5,290 exajoules), an amount only slightly lower than proven natural gas reserves and almost identical to the potential crude oil reserves expected from enhanced recovery methods.

Unconventional gas

BGR (1995) defines unconventional gas as natural gas derived from reservoirs not exploitable by conventional recovery techniques. Unconventional gas types include coalbed methane, tight formation gas, gas hydrates (clathrates), and aquifer (geopressured) gas. Regional estimates of unconventional gas occurrences in place are provided in table 5.4. The total resource potential exceeds 25,000 Tm^3 (960,000 exajoules).

Coalbed methane. Coalbed methane is a natural gas mixture containing more than 90 percent methane. It occurs primarily in high-rank coal seams from where it can migrate into the surrounding rock strata. Methane contents in coal seams can range from traces to 25 cubic metres per tonne of coal (Davidson, 1995). Regional resources of coalbed methane are genetically associated with the geographic distribution of bituminous coal and anthracite deposits. The former Soviet Union accounts for nearly 50 percent of recoverable resources, centrally planned Asia (including China) has about 20 percent, and North America has 15 percent.

Coalbed methane can be a by-product of underground coal mining or be produced for the methane exclusively. In fact, coalbed methane is an explosive hazard in underground mining operations and for safety reasons has traditionally been vented with mines' fresh air circulation. Since the 1970s methane captured from underground mining has increasingly been used to supplement local gas supplies. Thus methane capture and use can significantly mitigate greenhouse gas emissions because it avoids the release of methane—a potent greenhouse gas—and may replace fossil fuels with a higher carbon content. For long-term and stable methane supplies from coalbeds, however, dedicated drilling in coalbeds is more important than the methane from active underground coal mines.

Commercial coalbed methane production occurs only in the United States, contributing about 5 percent to natural gas production (BGR, 1998). But pilot projects are under way in a number of other countries, including Australia, China, India, Poland, Russia, Ukraine, and the United Kingdom. Estimates of methane resources range from 85–262 Tm^3 (BGR, 1995, 1998; Rice, Law, and Clayton, 1993). This assessment uses the BGR (1995) estimate of 233 Tm^3 (see table 5.4).

Tight formation gas. Tight formation gas is natural gas trapped in low-permeability reservoirs with in situ permeability of less than 0.1 millidarcy (mD), regardless of the type of the reservoir rock (Law and Spencer, 1993). Production of tight gas requires artificial stimulation

TABLE 5.3. ESTIMATED NATURAL GAS RESERVES

Region	Proven recoverable reserves (WEC, 1998)		Total recoverable reserves (WEC, 1998)		Proven and additional reserves (IGU, 2000)		Proven reserves (BP, 1999)		Enhanced gas recovery	
	Exajoules	Tm^3	Exajoules	Tm^3	Exajoules	Tm^3	Exajoules	Tm^3	Exajoules	Tm^3
North America	252	6.8	389	10.5	2,307	63.0	244	6.6	884	23.9
Latin America and Caribbean	303	8.2	426	11.5	1,556	42.5	298	8.0	306	8.3
Western Europe	181	4.9	300	8.1	436	11.9	177	4.8	306	8.3
Central and Eastern Europe	26	0.7	26	0.7	77	2.1	17	0.5	45	1.2
Former Soviet Union	2,087	56.4	2,583	69.8	5,767	157.5	2,112	56.7	1,923	52.0
Middle East and North Africa	2,076	56.1	2,250	60.8	5,343	149.5	2,065	55.4	1,421	38.4
Sub-Saharan Africa	155	4.2	155	4.2	238	6.5	161	4.3	93	2.5
Pacific Asia	207	5.6	207	5.6	798	21.8	196	5.3	158	4.3
South Asia	63	1.7	63	1.7	377	10.3	54	1.5	50	1.4
Centrally planned Asia	48	1.3	48	1.3	641	17.5	82	2.2	41	1.1
Pacific OECD	56	1.5	89	2.4	850	23.2	47	1.3	62	1.7
Total	**5,450**	**147.3**	**6,534**	**176.6**	**18,390**	**502.2**	**5,454**	**146.4**	**5,290**	**143.0**

TABLE 5.4. ESTIMATED UNCONVENTIONAL NATURAL GAS RESOURCE POTENTIAL IN PLACE

Region	Coalbed methane		Tight formation gas		Gas hydrates		Geopressured gas		Total unconventional gas	
	Exajoules	Tm^3	Exajoules	Tm^3	Exajoules	Tm^3	Exajoules	Tm^3	Exajoules	Tm^3
North America	2,898	78	518	14	80,575	2,178	109,964	2,972	193,955	5,242
Latin America and Caribbean	0	0	222	6	57,331	1,549	103,341	2,793	160,894	4,348
Western Europe	168	5	222	6	19,806	535	27,861	753	48,057	1,299
Central and Eastern Europe	126	3	37	1	0	0	6,623	179	6,786	183
Former Soviet Union	2,646	72	1,665	45	151,533	4,095	73,667	1,991	229,511	6,203
Middle East and North Africa	0	0	925	25	4,788	129	67,784	1,832	73,497	1,986
Sub-Saharan Africa	42	1	111	3	4,788	129	63,677	1,721	68,618	1,854
Pacific Asia	210	6	148	4	0	0	45,103	1,219	45,461	1,229
South Asia	42	1	37	1	4,788	129	17,427	471	22,294	602
Centrally planned Asia	2,058	56	333	9	0	0	27,824	752	30,215	817
Pacific OECD	420	11	37	1	23,857	645	56,166	1,518	80,480	2,175
Total	**8,610**	**233**	**4,255**	**114**	**347,467**	**9,391**	**599,437**	**16,201**	**959,769**	**25,940**

Source: BGR, 1995, 1998; Rogner, 1997.

techniques—such as massive hydraulic fracturing—to improve reservoir permeability. An advanced technique is horizontal drilling to develop tight gas formations, often in combination with massive hydraulic fracturing. These stimulation methods can achieve gas flow rates two to three times those of conventional vertical wells. In recent years about 3 percent of natural gas production has come from tight gas reservoirs.

Although tight gas reservoirs exist in many regions, only the tight gas resources in the United States have been assessed. The U.S. potential of tight gas resources from tight sandstone and Devonian shale reservoirs is 13.4 Tm^3 (BGR, 1995). BGR (1998) applies these U.S. estimates to extrapolate tight gas resource potential for other countries and regions, arriving at a global potential of 114 Tm^3 (see table 5.4).

Gas hydrates. IGU (1997) includes some unconventional gas in its definition of additional recoverable reserves—those that are at least of foreseeable economic interest and that may prove technically and economically recoverable with a reasonable level of confidence. This definition appears to exclude gas hydrates (clathrates). IGU (1997) notes that:

> Current scientific inquiries around the world are considering gas hydrates as a potential future supply of natural gas. The hydrates are frozen ice-like deposits that probably cover a significant portion of the ocean floor. The extent of their coverage and the high methane content of gas hydrates motivate speculation about the gigantic quantities of methane that could become available. At the present time there has been no attractive proposal for a technique to allow this methane to be recovered. Nor has there been any scientific confirmation of the quantities of methane that might be involved. Nevertheless, such investigations might bear fruit at some stage and radically alter current ideas regarding natural gas availability.

The existence of gas hydrates has been confirmed by direct evidence through sampling and by indirect evidence through geochemical and geophysical investigations. Samples have been recovered in 14 parts of the world; indirect evidence has been found in 30 others. Many oceanic occurrences have been inferred based on a special geophysical exploration technique—bottom-stimulating reflection. Resource estimates for gas hydrates are highly uncertain. BGR (1998) reports global clathrate occurrences of more than 9,000 Tm^3 (see table 5.4). Other estimates report clathrates as high as 20,000 Tm^3 (MacDonald, 1990 a, b; Collet, 1993).

There are no economically attractive technological proposals for recovering methane hydrates (box 5.2). But given their enormous resource potential, it is plausible to expect that extraction methods will eventually be developed if long-term global gas demand warrants clathrate recovery. Research projects are under way in India, Japan, and the United States to examine the viability of gas hydrate recovery (Collet and Kuuskraa, 1998; BGR, 1998).

The differences between static and dynamic views of oil resources can be partly explained by the way the different schools view unconventional oil.

Aquifer (geopressured) gas. In many parts of the world, natural gas is found dissolved in aquifers under normal hydrostatic pressure, primarily in the form of methane (Marsden, 1993). This unconventional gas is also referred to as hydropressured gas or brine gas. The amount of gas dissolved in underground liquids increases substantially with depth. At depths up to 4,000 metres, 0.5–1.5 cubic metre of gas is dissolved per metre of water in aquifers. This gas factor jumps to 7–20 at depths of 7,000–8,000 metres (BGR, 1995).

Aquifer gas is expected to occur in nearly all sedimentary basins (Marsden, 1993). While no detailed assessment of aquifer gas resources is available, BGR (1998) derives potential aquifer gas in place from the groundwater volume contained in high-permeability sand stones in the hydrosphere. This approach leads to an estimate of 2,400–30,000 Tm^3 of geopressured gas in place, with a mean estimate of 16,200 Tm^3. In the absence of a more detailed assessment, a practical approach had to be taken in delineating regional resource quantities. The regional breakdown in table 5.4 was obtained by weighting the global mean estimate of gas occurrence in place with regional shares of total sedimentary area.

While these estimates of aquifer gas occurrences are highly speculative, the potential quantities are staggering. Even a future recovery factor of 5 percent implies a resource volume five times the conventional reserves estimates of BP. Aquifer gas is already produced in small quantities from shallow reservoirs in Italy, Japan, and the United States. But in all cases aquifer gas recovery has been motivated by the production of trace elements (such as iodine) rather than by the gas itself.

Coal reserves and resources

Coal deposits can be found in sedimentary basins of various geological ages. Mineable coal deposits require a minimum seam thickness over a sufficiently large area. Coal production occurs in open-pit extraction or underground mining. Coal resource estimates are generally based on drill-hole tests and geological observations. Coal is subdivided into several broadly defined types according to their caloric values. Generally, the types are bituminous coal (including anthracite), sub-bituminous coal, and lignite. For practical purposes, the subdivision is based on energy content, with the value of 16,500 kilojoules per kilogram as demarcation between hard coal (bituminous and high-energy sub-bituminous coals) and soft brown coal (lignite and low-energy sub-bituminous coals).

For almost 200 years coal has provided the basis for energy production as well as iron and steel manufacturing. It also fuelled the industrial revolution of the 19th century. In the 20th century—mainly after World War II—coal lost its leading position to crude oil. But the welfare and economic development of many countries continue to be based on coal. Coal provides about 22 percent of the world energy supply and is the most important fuel for electricity generation. About 40 percent of global electricity is produced in coal-fuelled power stations.

Coal will likely contribute substantially to the future world energy supply. Assuming no intervention policies targeted at preventing climate change, projections by IEA (1998c) and Nakićenović, Grübler, and McDonald (1998) show global coal production increasing from 2.4 gigatonnes of oil equivalent (Gtoe) in 1995 to 4.0 Gtoe by 2020. Given its enormous proven reserves, the current rate of coal production could continue well into the future.

The size of coal resources is not a restraining factor to its use throughout the 21st century. Rather, continued coal use will depend on the timely development of production facilities and related infrastructure, given lead times of up to five years for open-cast operations and drift mines. Nevertheless, there is considerable potential for a significant increase in coal production capacity in the short to medium term. Although environmental considerations may limit coal use with current combustion technologies, advanced conversion technology—with carbon abatement and disposal—may create new market opportunities (see chapter 8).

Current resources and reserves

World coal resources in place are estimated at more than 7,400 billion tonnes of coal, or about 4,470 Gtoe (WEC 1998). The recoverable portion is estimated at roughly 500 Gtoe, which corresponds to the amount generally labelled reserves. About

BOX 5.2. ARE GAS HYDRATES AN EXPLOITABLE ENERGY RESOURCE?

A gas hydrate is a crystalline cage of water molecules that can trap various gases. Hydrates can form under conditions of high pressure and low temperatures. Methane hydrates exist in polar permafrost and in sediments below the ocean floor where conditions are appropriate. Hydrates will not exist below a depth where the reservoir temperature is too high for their stability. But solid hydrate layers can provide top seals for reservoirs of free methane that can accumulate beneath. Offshore methane hydrate deposits have been identified near the coasts of many countries—including countries (such as Japan) otherwise poor in fossil fuels.

The amount of methane associated with hydrates is highly uncertain, but the quantities are probably far greater than conventional oil and gas resources combined. Estimates of global methane hydrate resources range from 0.1–300 million exajoules (Collet and Kuuskraa, 1998; Max, Pellanbarg, and Hurdle, 1997). How much can be practically and affordably recovered is also highly uncertain (USDOE, 1998). An emerging view is that free gas trapped beneath solid hydrate layers will be easier to recover than gas in hydrates (Max, Pellanbarg, and Hurdle, 1997). Free gas recovery would depressurise the reservoir, leading to hydrate melting at the hydrate– free gas interface and thus to free gas replenishment. The process could continue as long as the hydrate layer remains thick enough to cap the free gas below. Preliminary (though dated) estimates for recovering methane at favourable sites suggest that it might not be significantly more costly than recovering conventional natural gas (Holder, Kamath, and Godbole, 1984). But even if this proves accurate, getting the gas to major markets could often be quite costly because of high transport costs, since hydrate deposits are often far from such markets.

85 percent of the resources in place are classified as bituminous or sub-bituminous (hard) coal; the rest is lignite (soft brown) coal. (Similar proportions apply to reserves.)

Three-quarters of global coal reserves are in Australia, China, India, South Africa, and the United States. Among regions, North America has the largest coal reserves (table 5.5). Substantial reserves are also available in the former Soviet Union and in South Asia. The European share has to be viewed with caution because reserves may soon be declassified to resources (neutral stuff) as production subsidies are eliminated and industry begins to close unprofitable operations.

In 1997 global coal production totalled 2,310 Gtoe, 91 percent of which was hard coal. China was the largest producer of hard coal (31 percent of the world total), followed by the United States (26 percent), India (7 percent), Australia (6 percent), and South Africa (6 percent). All other producers hold shares of less than 5 percent.

Almost 90 percent of world coal production is used domestically. In 1997 the 10 largest coal exporters traded about 500 million tonnes of hard coal. The largest exporter was Australia with a traded share of about 30 percent, followed by the United States with 15 percent.

Projections show global coal production increasing from 2.4 Gtoe in 1995 to 4.0 Gtoe by 2020.

TABLE 5.5. ESTIMATED COAL RESERVES (MILLIONS OF TONNES)

Region	Bituminous (incl. anthracite)	Sub-bituminous	Lignite	Total (exajoules)
North America	115,600	103,300	36,200	6,065
Latin America and Caribbean	8,700	13,900	200	533
Western Europe	26,300	600	47,700	1,178
Central and Eastern Europe	15,400	5,500	10,700	744
Former Soviet Union	97,500	113,500	36,700	4,981
Middle East and North Africa	200	20	0	6
Sub-Saharan Africa	61,000	200	< 100	1,465
Pacific Asia	900	1,600	5,100	10
South Asia	72,800	3,000	2,000	1,611
Centrally planned Asia	62,700	34,000	18,600	2,344
Pacific OECD	48,100	2,000	41,600	1,729
Total	**509,200**	**277,600**	**198,900**	**20,666**

Source: WEC, 1998.

Additional resources

WEC (1998) also provides information on coal resources by type. But because of incomplete country coverage, no regional or global aggregates are given. BGR (1995) estimated global coal resources at 5,000 Gtoe, of which 4,600 Gtoe are hard coal.

In a 1998 update, BGR revised the estimate for additional coal resources in place to 4,300 Gtoe billion, of which about 3,500 Gtoe are additional hard coal resources. The Russian Federation has the largest share—about 2,100 Gtoe of hard coal. About 80 percent of the additional resources in the Russian Federation are in remote areas of Siberia. Large investments for infrastructure and development limit the conversion of these resources into reserves. Because of the large reserves, there is no immediate need for additional investigation of the resource potential world-wide. Estimates of the regional distribution of world total resources (including reserves) are shown in table 5.6.

Summary of fossil resources

Fossil fuel reserves, resources, and additional occurrences are shown relative to cumulative consumption and current (1998) use in table 5.7. For an analysis that extends well into the 21st century and explores the long-term availability of fossil resources, the fossil resource base is the relevant yardstick. The resource base for conventional and unconventional oil and gas is large enough to last comfortably for another 50–100 years—and possibly much longer—essentially at prices not much different from today. This projection assumes that past hydrocarbon productivity gains in the upstream sector can be maintained and that these resources remain in demand.

Tapping into the vast fossil resource base may eventually become a transportation challenge. For one thing, fossil resources are not evenly distributed around the globe. For another, the location of many unconventional oil and, more important, gas occurrences is far from the centres of energy demand. In China and India coal delivery costs (for rail transport) already approach production costs. Transportation logistics and costs may affect the economic attractiveness of remote resource sites. Long-distance and trans-boundary energy transport raises concerns about the security of energy supply (see chapter 4).

The fossil resource data in table 5.7 are also shown in terms of their carbon content. Since the onset of the industrial revolution, 296 gigatonnes of carbon contained in fossil fuels have been oxidised and released to the atmosphere. The resource base represents a carbon volume of some 6,500 gigatonnes of carbon. The 296 gigatonnes of carbon emitted to the atmosphere already raise concerns about climate stability—and humankind has the means to add several times that amount during the 21st century. Fossil resource scarcity will not come to the rescue. Nakićenović, Grübler, and McDonald (1998) indicate that between 1990 and 2100 emissions under the A2 scenario (see chapter 9) of some 1,600 gigatonnes of carbon—

roughly the carbon content of conventional fossil reserves (see table 5.7)—could raise the atmospheric concentration of carbon dioxide to 750 parts per million by volume (ppmv). (Before the industrial revolution, carbon dioxide concentrations were 280 ppmv; today they are 360 ppmv.) The corresponding increase in global mean temperature could be 2.0–4.5 Kelvin.[5]

Since 1973 the tradable price of oil (the 'marker' for competing fuels) has been much higher than the marginal cost of the highest-cost producer, reflecting geopolitics and a lack of competing fuels. Today the highest marginal cost of production is less than $10 a barrel—and in the Gulf it is just $2–3 a barrel (Rogner, 1997; Odell, 1998). Economic rent accounts for the rest of the tradable price. This rent could be reduced if competing fuels—unconventional oil, synliquids from gas or coal, renewable or nuclear energy—could equal the marginal cost of production. Thus the true cost of oil for the entrance of competitors is less than $10 a barrel. This cost level has already been achieved by some producers of unconventional oil and gas—tar sands in Alberta (Chadwick, 1998), heavy oil in Venezuela (Aalund, 1998), coalbed methane in the United States (BGR, 1998). The question then is, can technological advances balance the higher costs of more difficult production? Experience suggests that the answer is probably yes in the long run. But in the Gulf, marginal costs are unlikely to exceed $5–$10 a barrel even in the long term.

One question of interest to many upstream investment planners is, when will the call on unconventional fossil occurrences commence? To some extent it is already here. Alberta's tar sand production started more than 30 years ago and, after some difficulties in the wake of the oil price collapse of 1986, it is now competitive in today's markets. Venezuela's heavy oil has also been produced for many years. Still, the share of unconventional oil—and, for that matter, natural gas—is only about 6 percent of world production.

The future production profile of unconventional oil will be a function of the demand for oil products, the price and availability of conventional oil, and the cost and availability of oil substitutes. So what are the prospects for future conventional oil production? The answer is by no means conclusive. The February 1998 issue of the *Explorer,* the journal of the American Association of Petroleum Geologists, writes that "it is not comforting that experts disagree on almost every aspect of the world outlook, from annual production to current reserves to projected energy demand…One majority

TABLE 5.6. ESTIMATED COAL RESOURCES (BILLIONS OF TONNES OF COAL EQUIVALENT)

Region	Hard coal	Soft coal/ lignite	Total (exajoules)
North America	674	201	25,638
Latin America and Caribbean	37	2	1,143
Western Europe	337	11	10,196
Central and Eastern Europe	106	14	3,516
Former Soviet Union	3,025	751	110,637
Middle East and North Africa	1	1	58
Sub-Saharan Africa	181	< 1	5,303
Pacific Asia	7	5	352
South Asia	84	1	2,491
Centrally planned Asia	429	35	13,595
Pacific OECD	139	67	6,030
Total	**5,021**	**1,089**	**178,959**

Note: Includes reserves. *Source: BGR, 1998.*

TABLE 5.7. AGGREGATE FOSSIL ENERGY OCCURRENCES

Type	Consumption 1860–1998		Consumption 1998		Reserves		Resources[a]		Resource base[b]		Additional occurrences	
	Exajoules	Gigatonnes of carbon	Exajoules	Gigatonnes of carbon	Exajoules	Gigatonnes of carbon	Exajoules	Gigatonnes of carbon	Exajoules	Gigatonnes of carbon	Exajoules	Gigatonnes of carbon
Oil												
Conventional	4,854	97	132.7	2.65	6,004	120	6,071	121	12,074	241		
Unconventional	285	6	9.2	0.18	5,108	102	15,240	305	20,348	407	45,000	914
Natural gas[c]												
Conventional	2,346	36	80.2	1.23	5,454	83	11,113	170	16,567	253		
Unconventional	33	1	4.2	0.06	9,424	144	23,814	364	33,238	509	930,000	14,176
Coal	5,990	155	92.2	2.40	20,666	533	179,000	4,618	199,666	5,151	n.a.	
Total	**13,508**	**294**	**319.3**	**6.53**	**46,655**	**983**	**235,238**	**5,579**	**281,893**	**6,562**	**975,000**	**15,090**

a. Reserves to be discovered or resources to be developed as reserves. b. The sum of reserves and resources. c. Includes natural gas liquids.

Source: Compiled by author from tables 5.1–5.6.

opinion emerges: Sometime in the coming century, world-wide production of petroleum liquids will reach a peak and then begin to decline…[but] there is little agreement about when this will happen, and how steep or gradual the decline will be".

Sometime in the coming century, world-wide production of petroleum liquids will reach a peak and then begin to decline.

Assuming ultimately recoverable conventional oil resources of, say, 400 gigatonnes and a demand development of about 1.5 percent a year, conventional oil production will peak around 2030 (reach the depletion mid-point) with an annual production of 4.4 gigatonnes, up from 3.5 gigatonnes in 1998. Total oil demand, however, would run at 5.8 gigatonnes—implying that unconventional oil will account for 1.4 gigatonnes (Odell, 1998). In other words, unconventional sources will have to be tapped speedily during the first decade of the 21st century. But experience with unconventional oil production shows a long gestation period and high threshold costs of up to $30 a barrel. Most oil price projections for 2010 (which have an extremely poor track record) expect oil prices of $13–$29 a barrel.

Thus accelerated expansion of unconventional oil production (primarily tar sands in Alberta and extra heavy oil in Venezuela and Russia) hinges on:

- Short-term developments in oil prices.
- Actual developments in demand.
- Technological progress in field growth for conventional occurrences.
- Technological advances in the production of unconventional occurrences.
- The risk attitude of investors in unconventional production capacity.

Current market prospects for unconventional oil production remain modest at best. But this may change drastically—for example, changing geopolitics could raise oil prices high enough to facilitate investments in unconventional oil. In general, most oil market outlooks project a steady increase in OPEC's share in global oil production.

TABLE 5.8. REASONABLY ASSURED URANIUM RESOURCES RECOVERABLE AT LESS THAN $80 A KILOGRAM (RESERVES) AND AT $80–130 A KILOGRAM (TONNES OF URANIUM)

Region	< $80 a kilogram[a]	$80–130 a kilogram	Total
North America	420,000	251,000	671,000
Latin America and Caribbean	136,400	5,600	142,000
Western Europe	37,300	53,500	90,800
Central and Eastern Europe	14,000	25,800	39,800
Former Soviet Union	564,300	210,200	774,500
Middle East and North Africa	21,000	8,400	29,400
Sub-Saharan Africa	453,600	96,000	549,600
Pacific Asia	0	16,800	16,800
South Asia	5,000	52,000	57,000
Centrally planned Asia	49,300	65,300	114,600
Pacific OECD	615,000	99,600	714,600
Total	**2,315,900**	**884,200**	**3,200,100**

a. Adjusted for mining and milling losses and production of 1997.

Source: NEA and IAEA, 1997.

Reserves and resources of fissile materials

Naturally occurring fissile materials—natural uranium and thorium—can be found in various types of geological deposits. Although they may occur jointly, most uranium and thorium reside in separate deposits. Like fossil occurrences, uranium and thorium are finite in the Earth's crust, and recoverable quantities depend on demand and market conditions, type of deposit, and technology.

During the 1970s, when large increases in uranium demand before the turn of the century were expected, the recovery of low-concentration uranium from seawater was investigated. Although technically feasible, estimated production costs appeared prohibitively high relative to alternatives. More recent research and development indicate that the costs of recovering uranium from seawater have fallen considerably, but are still too high given current and expected market prices for uranium. With the declining demand for uranium, recovery is concentrated on terrestrial deposits where uranium availability is estimated according to different production cost categories—such as recoverable at less than $40 a kilogram, less than $80 a kilogram, and less than $130 a kilogram.

Due to the limited development of thorium-fuelled reactors, little effort has been made to explore and delineate thorium. But reserves and resources are known to exist in substantial quantities.

The resource outlook presented below is based on a 'once-through fuel cycle' of uranium in normal power reactors—that is, 'burner' reactors. But the supply of raw material for reactor fuel is determined not only by uranium presently mined but also by fissile material initially produced for military purposes, which since the mid-1990s has become available for civil use. Reprocessed uranium and plutonium are additional supply sources with the capacity to displace up to 30 percent of the initial demand through recycling.

Uranium reserves

Uranium reserves are periodically estimated by the Organisation for Economic Co-operation and Development's Nuclear Energy Agency (NEA) together with the International Atomic Energy Agency (IAEA), Uranium Institute (UI), World Energy Council (WEC), and numerous national geological institutions. Although these organisations use different reserve and resource definitions, the differences between their estimates are usually insignificant.

Because NEA-IAEA estimates have the widest coverage, the reserves reported in their latest survey are reported here (NEA-IAEA, 1997). The two organisations define as reserves those deposits that could be produced competitively in an expanding market. This category is called reasonably assured resources and includes uranium occurrences that are recoverable at less than $80 a kilogram. (Because of declining market prospects, a number of countries have begun to report estimates of reasonably assured uranium resources at less than $40 a kilogram.[6]) Uranium reserves are estimated at 2.3 million tonnes (table 5.8). These reserves are sufficient to meet the demand of existing and planned nuclear power plants well into the 21st century.

The fission of 1 kilogram of natural uranium produces about 573 gigajoules of thermal energy—some 14,000 times as much as in 1 kilogram of oil. But this is still only a small fraction of the energy potentially available from the uranium; up to 100 times this amount can be derived in a fast neutron reactor (a technology that is well developed but not commercially viable). In today's plants, 22 tonnes of uranium are typically needed to produce 1 terawatt-hour of electricity.

Uranium resources

Uranium resources are classified according to the degree of their geological assurance and the economic feasibility of their recovery. Resources that cost less than $80 a kilogram to recover (that is, reasonably assured resources) are considered reserves. Under higher market price assumptions, reasonably assured resources recoverable at less than $130 a kilogram would also qualify as reserves. Resources beyond these categories have been estimated, but with a lower degree of geological assurance. NEA-IAEA (1997) define two categories of estimated additional resources, EAR-I and EAR-II.[7] Another resource category, speculative resources, is also applied. While reasonably assured resources and EAR-I include known or delineated resources, EAR-II and speculative resources have yet to be discovered (table 5.9). Global conventional uranium reserves and resources total about 20 million tonnes.

In addition, vast quantities of unconventional uranium resources exist, essentially low-concentration occurrences that were of temporary interest when medium-term demand expectations for uranium were thought to exceed known conventional resources. Such unconventional resources include phosphate deposits with uranium concentrations of 100–200 parts per million in sedimentary rocks, and in exceptional conditions more than 1,000 parts per million in igneous rocks. The uranium content of the world's sedimentary phosphates is estimated at nearly 15 million tonnes, more than half of them in Morocco. To date the only way to extract uranium on an industrial basis, demonstrated mainly in the United States, is through recovery from phosphoric acid. This liquid-liquid separation process uses solvent to extract uranium, allowing for the recovery of up to 70 percent of the uranium contained in the ore. Globally, phosphoric acid plants have a theoretical capacity of supplying about 10,000 tonnes of uranium a year, provided economic conditions can be met.

Other unconventional uranium resources that have been explored are black shale deposits and granite rocks with elevated uranium concentrations. Although their estimated theoretical resource potential is substantial, exploration and extraction have been limited to experimental scales. The low uranium content and potential environmental challenges associated with the production of these occurrences have led to the termination of all efforts. Another low-concentration source of uranium is the vast amount contained in seawater—about 4.5 billion tonnes at 3 parts per billion, often seen as an eventual 'back-stop' uranium resource (box 5.3).

TABLE 5.9. ESTIMATED ADDITIONAL AMOUNTS AND SPECULATIVE RESOURCES OF URANIUM (TONNES OF URANIUM)

Region	Estimated additional amount[a]	Speculative resources
North America	2,559,000	2,040,000
Latin America and Caribbean	277,300	920,000
Western Europe	66,900	158,000
Central and Eastern Europe	90,900	198,000
Former Soviet Union	914,000	1,833,000
Middle East and North Africa	12,000	40,000
Sub-Saharan Africa	852,800	1,138,000
Pacific Asia	5,000	0
South Asia	46,000	17,000
Centrally planned Asia	96,500	3,183,000
Pacific OECD	180,000	2,600,00
Total	**5,100,400**	**12,127,000**

a. Includes reasonably assured resources at extraction costs of $130–260 a kilogram as well as estimated additional resource categories I and II at less than $260 a kilogram.

Source: NEA and IAEA, 1997.

BOX 5.3 URANIUM FROM SEAWATER

Seawater contains a low concentration of uranium—less than 3 parts per billion. But the quantity of contained uranium is vast—some 4.5 billion tonnes, or 700 times known terrestrial resources recoverable at less than $130 a kilogram. It might be possible to extract uranium from seawater at low cost. Early research in Japan suggested that it might be feasible to recover uranium from seawater at a cost of $300 a kilogram of uranium (Nobukawa and others, 1994). More recent work in France and Japan suggests that costs might be as low as $80–100 a kilogram (Charpak and Garwin, 1998; Garwin, 1999). But these estimates are based on methods used to recover gram quantities of uranium, and unforeseen difficulties may arise in scaling up these methods a million-fold or more. The implications of developing this uranium recovery technology are discussed in chapter 8.

Hydro energy is not evenly accessible, and sizeable hydro resources are often remotely located.

Thorium reserves and resources

Thorium-fuelled burner and breeder reactors were developed in the 1960s and 1970s but fell behind thereafter due to lower than expected market penetration of nuclear power and to a focus on advancing uranium-fuelled nuclear power technologies. Moreover, thorium is not readily useable in a nuclear reactor because the number of neutrons released in each fission makes it difficult to sustain the chain reaction. India has far more thorium than uranium resources, and is attempting to develop the thorium fuel cycle. Important commercial developments of reactors using thorium have not materialised elsewhere. But high-temperature, gas-cooled reactors, like the one in South Africa, could also use a thorium-based fuel cycle. Thorium resources are widely available and could support a large-scale thorium fuel cycle. But given the global availability of inexpensive uranium, thorium-fuelled reactors are unlikely to be significant in resource terms in the next 50 years.

Monazite, a rare-earth and thorium phosphate mineral, is the primary source of thorium. In the absence of demand for rare-earth elements, monazite would probably not be recovered for its thorium content. Other ore minerals with higher thorium contents, such as thorite, would be more likely sources if demand increased significantly. But no thorium demand is expected. In addition, world-wide demand for thorium-bearing rare-earth ores remains low. Thorium disposal is the primary concern in obtaining mining permits for thorium-containing ores. Reserves exist primarily in recent and ancient placer deposits. Lesser quantities of thorium-bearing monazite reserves occur in vein deposits and carbonatites.

Thorium resources occur in provinces similar to those of reserves. The largest share is contained in placer deposits. Resources of more than 500,000 tonnes are contained in placer, vein, and carbonatite deposits.

Global thorium reserves and resources outside the former Soviet Union and China are estimated at 4.5 million tonnes, of which about 2.2 million tonnes are reserves (table 5.10). Large thorium deposits are found in Australia, Brazil, Canada, Greenland, India, the Middle East and North Africa, South Africa, and the United States. Disseminated deposits in other alkaline igneous rocks contain additional resources of more than 2 million tonnes.

TABLE 5.10. ESTIMATED THORIUM RESERVES AND ADDITIONAL RESOURCES (TONNES OF THORIUM)

Region	Reserves	Additional resources
North America	258,000	402,000
Latin America and Caribbean	608,000	702,000
Western Europe	600,000	724,000
Central and Eastern Europe	n.a.	n.a.
Former Soviet Union	n.a.	n.a.
Middle East and North Africa	15,000	310,000
Sub-Saharan Africa	38,000	146,000
Pacific Asia	24,000	26,000
South Asia	319,000	4,000
Centrally planned Asia	n.a.	n.a.
Pacific OECD	300,000	40,000
Total	**2,162,000**	**2,354,000**

n.a. Not available. *Source: BGR Data Bank.*

Hydroelectric resources

Hydroelectricity, which depends on the natural evaporation of water by solar energy, is by far the largest renewable resource used for electricity generation. In 1997 hydroelectricity generation totalled 2,566 terawatt-hours (IEA, 1999). Water evaporation per unit of surface area is larger for oceans than for land and, assisted by wind, is the principal cause of the continuous transfer of water vapour from oceans to land through precipitation. The maintenance of a global water balance requires that the water precipitated on land eventually returns to the oceans as runoff through rivers.

As with all renewable resources, the amount of water runoff is finite for a defined amount of time but, all else being equal, this finite amount is forever available. By applying knowledge of the hydrological cycle, the world-wide amount of runoff water can be assessed quite accurately. Hydroelectricity is obtained by mechanical conversion of the potential energy of water. An assessment of its energy potential requires detailed information on the locational and geographical factors of runoff water (available head, flow volume per unit of time, and so on).

Because rainfall varies by region and even country, hydro energy is not evenly accessible. Moreover, sizeable hydro resources are often remotely located. As a result of advances in transmission technology and significant capital spending, electricity is being delivered to places far from the generation stations, making energy from water more affordable to more people. Projects considering the connection of electric grids between countries, regions, and even continents have been implemented or are planned (Moreira and Poole, 1993).

Although hydroelectricity is generally considered a clean energy source, it is not totally devoid of greenhouse gas emissions, ecosystem burdens, or adverse socioeconomic impacts (see chapter 3). For comparable electricity outputs, greenhouse gas emissions associated with hydropower are one or two orders of magnitude lower than those from fossil-generated electricity. Ecosystem impacts usually occur downstream and range from changes in fish biodiversity and in the sediment load of the river to coastal erosion and pollution

(McCulley, 1996). Potentially adverse socio-economic aspects of hydroelectricity include its capital intensity and social and environmental impacts (McCulley, 1996). Capital-intensive projects with long construction and amortisation periods become less attractive in privatising markets. Higher education levels and increasing population densities along river beds substantially raise the socioeconomic costs of relocation. Local environmental issues require more thorough management than before because modern communications and determined citizen groups can easily turn a remote or local problem into a global issue that can influence international capital and financing markets. Large hydropower projects increasingly encounter public resistance and, as a result, face higher costs.

Integration aspects may increase the competitiveness of hydroelectricity because of its quick response to fluctuations in demand. When hydropower provides spinning reserve and peak supply, this ability allows thermal electric plants to operate closer to their optimal efficiency, lowering fuel costs and reducing emissions from burning fossil fuels. Pump storage might absorb off-peak power or power from intermittent supplies for peak use at a later point.

Theoretical potential

The world's annual water balance is shown in table 5.11. Of the 577,000 cubic kilometres of water evaporating from ocean and land surfaces, 119,000 cubic kilometres precipitate on land. About two-thirds is absorbed in about equal parts by vegetation and soil; the remaining third becomes runoff water. Most of the fraction absorbed by vegetation and soil evaporates again and amounts to 72,000 cubic kilometres. The difference of 47,000 cubic kilometres is, in principle, available for energy purposes.

The amount of inland precipitation varies slightly by continent, from 740–800 millimetres a year. The two exceptions are South America (1,600 millimetres a year) and Antarctica (165 millimetres). Thus runoff water per unit of land area in South America is at least two times that elsewhere.

Convolution of runoff water volumes with average altitudes allows for the evaluation of theoretical hydropower potential by region (table 5.12). Asia (including Pacific Asia, South Asia, and centrally planned Asia) has the largest potential, because its average altitude of 950 metres is the highest of all continents (except Antarctica, which has an average altitude of 2,040 metres). But average altitudes are insufficient for calculating theoretical hydropower potential—runoff is not evenly distributed across a continent. In addition, seasonal variations in runoff influence theoretical potentials. Estimates of the global theoretical hydroelectricity potential range from 36,000–44,000 terawatt-hours a year (Raabe, 1985; Boiteux, 1989; Bloss and others, 1980; *World Atlas and Industry Guide,* 1998).

The global water balance and regional precipitation patterns may change as a result of climate change. Current models suggest that global precipitation will increase but that regional precipitation patterns will shift. These changes will affect global hydropower potential.

Technical potential

Appraisals of technical potential are based on simplified engineering criteria with few, if any, environmental considerations. Although the technical potential should exclude economic aspects, these appear to be inherent in such appraisals. Evaluation criteria may differ substantially by country and, especially in developing countries, may be quite unsophisticated. Reported technical potentials could be inflated or, because of incomplete assessments, seriously underestimated (Bloss and others, 1980; *International Water Power and Dam Construction,*

TABLE 5.11. ANNUAL WORLD WATER BALANCE

Region	Surface area 10^6 km^2	Precipitation		Evaporation		Runoff[a]	
		Millimetres	Thousands of cubic kilometres	Millimetres	Thousands of cubic kilometres	Millimetres	Thousands of cubic kilometres
Europe	10.5	790	8.3	507	5.3	283	3.0
Asia	43.5	740	32.2	416	18.1	324	14.1
Africa	30.1	740	22.3	587	17.7	153	4.6
North America	24.2	756	18.3	418	10.1	339	8.2
South America	17.8	1,600	28.4	910	16.2	685	12.2
Australia and Oceania	8.9	791	7.1	511	4.6	280	2.5
Antarctica	14.0	165	2.3	0	0.0	165	2.3
Total/average)	149	800	119	485	72	315	47.0
Pacific Ocean	178.7	1,460	260.0	1,510	269.7	-83	-14.8
Atlantic Ocean	91.7	1,010	92.7	1,360	124.4	-226	-20.8
Indian Ocean	76.2	1,320	100.4	1,420	108.0	-81	-6.1
Arctic Ocean	14.7	361	5.3	220	8.2	-355	-5.2
Total/average	361	1,270	458	1,400	505	-130	-47.0
Globe	**510**	**1,130**	**577**	**1,130**	**577**	**0**	**0**

a. Outflow of water from continents into oceans.

Source: UNESC, 1997.

1989; *World Atlas and Industry Guide,* 1998).

Most significant are the differences in theoretical, technical, and economic potential by region, especially for Africa, North America, and the former Soviet Union (figure 5.3).[8] In general, total technical potential has not been fully measured for most developing countries. In Brazil, for example, hydroelectricity is responsible for 96 percent of electricity generation. Of the 260 gigawatts of technical hydropower potential, more than one-third is accounted as estimated. Of that, 32 gigawatts have never been individually analysed (ANEEL, 1999).

Technological advances tend to increase the technical potential and so broaden the prospects for hydropower meeting future electricity requirements. Improvements in the efficiency and utility of turbines for low-head and small hydro sites permit more effective use of a larger number of sites in a less environmentally intrusive manner. Advances in adjustable-speed generation and new large turbines enable the rehabilitation and expansion of existing capacities (Churchill, 1997). Refurbishment of plants has shown that advanced technologies can significantly increase the energy output at essentially unchanged primary water flows (*International Water Power and Dam Construction,* 1989; Taylor, 1989). In addition, technological improvements enable the use of previously uneconomical potentials and new sites.

Large hydropower projects increasingly encounter public resistance and, as a result, face higher costs.

But hydroelectric generation is a mature technology for which most components are nearing their practically achievable maximum. As a result further improvements in performance are expected to be modest. Average efficiencies of existing plants are about 85 percent; a 10 percentage point increase would be a major accomplishment.

Economic potential

The economic potential of hydropower is based on detailed economic, social, environmental, geological, and technical evaluations.[9] It is by far the most difficult potential to establish because the financial, environmental, and social parameters that determine it are driven by societal preferences that are inherently difficult to project.

One approach is to use the historically observed fraction of the technical potential used in industrialised countries with extensive hydropower developments. Western Europe has developed 65 percent of its technical hydropower potential, and the United States has developed

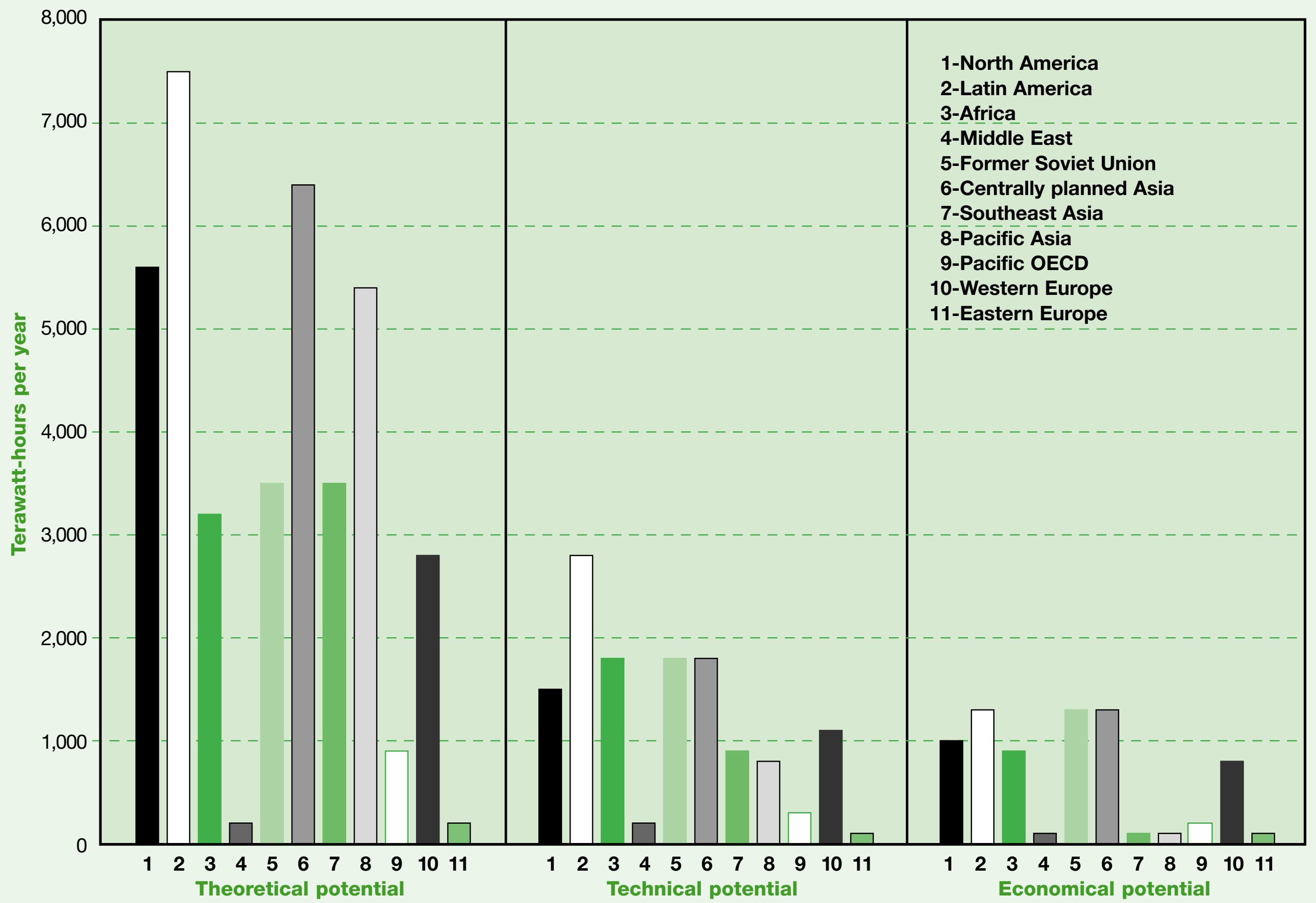
TABLE 5.12. THEORETICAL, TECHNICAL, AND ECONOMIC HYDROELECTRIC POTENTIALS, INSTALLED CAPACITIES, AND CAPACITIES UNDER CONSTRUCTION, 1997 (TERAWATT-HOURS UNLESS OTHERWISE INDICATED)

Region	Gross theoretical potential	Technical potential	Economic potential	Installed hydro capacity (gigawatts)	Hydropower production	Hydro capacity under construction (megawatts)
North America	5,817	1,509	912	141	697	882
Latin America and Caribbean	7,533	2,868	1,199	114	519	18,331
Western Europe	3,294	1,822	809	16	48	2,464
Central and Eastern Europe	195	216	128	9	27	7,749
Former Soviet Union	3,258	1,235	770	147	498	6,707
Middle East and North Africa	304	171	128	21	66	1,211
Sub-Saharan Africa	3,583	1,992	1,288	66	225	16,613
Pacific Asia[a]	5,520	814	142	14	41	4,688
South Asia[a]	3,635	948	103	28	105	13,003
Centrally planned Asia	6,511	2,159	1,302	64	226	51,672
Pacific OECD	1,134	211	184	34	129	841
Total	**40,784**	**13,945**	**6,964**	**655**	**2,582**	**124,161**
Total[b]	**40,500**	**14,320**	**8,100**	**660**	**2,600**	**126,000**

a. Several countries in Pacific Asia and South Asia do not publicise their economic potential. As a result the reported economic potentials for the regions are too low—and in South Asia the economic potential is even lower than the electricity generated. b. These are the values listed in the source. They differ from the total in the previous row due to typographical errors and due to the inclusion of estimations for countries for which data are not available.

Source: World Atlas and Industry Guide, 1998.

FIGURE 5.3 GLOBAL THEORETICAL, TECHNICAL, AND ECONOMIC HYDROELECTRIC POTENTIALS (TERAWATT-HOURS A YEAR)



Source: World Atlas and Industry Guide, 1998.

76 percent (*World Atlas and Industry Guide,* 1998). A utilisation rate of 40–60 percent of a region's technical potential is a reasonable assumption and leads to a global economic hydroelectricity potential of 6,000–9,000 terawatt-hours a year. More detailed analysis based on current technological and economic puts the global economic potential at 8,100 terawatt-hours a year (see table 5.12).

Major constraints to hydroelectricity expansion

Physical constraints. Global water runoff is 47,000 cubic kilometres a year, 28,000 cubic kilometres of which is surface runoff and 13,000 of which is stable underground flow into rivers (L'vovich, 1987). Only about three-quarters of the stable underground flow (9,000 cubic kilometres) is easily accessible and economically usable (WRI, 1998). In addition, 3,000 cubic kilometres of useful capacity is available in form of human-made lakes and reservoirs (L'vovich, 1987). Global anthropogenic water withdrawals are about 27 percent of total availability, or 3,250 cubic kilometres a year. Agriculture accounts for 65 percent of the diverted water, industries for 24 percent, and households and other municipal users for 7 percent, while 4 percent is evaporated from reservoirs (Shiklomanov, 1993).

Water use in agriculture totals 2,300 cubic kilometres a year and is expected to increase with growing food demand. The United Nations projects a 50–100 percent increase in irrigation water by 2025 (Raskin and others, 1997). Most of the projected increase in water demand will occur in developing countries because of rapid growth in population, industry, and agriculture. Water pollution adds enormously to local and regional water scarcity by eliminating large volumes from the available supply. Many developing countries undergoing rapid industrialisation face the full range of modern toxic pollution problems—eutrophication, heavy metals, acidification, and persistent organic pollutants (WHO, 1997).

Globally, water supplies are abundant. But they are unevenly distributed among and within countries. In some areas water withdrawal has reached such dimensions that surface water supplies are

Biomass-derived fuels can substitute for fossil fuels in existing energy supply infrastructure without contributing to the build-up of greenhouse gases.

shrinking and groundwater reserves are being depleted faster than they can be replenished by precipitation (WHO, 1997). One-third of the world's people live in countries experiencing moderate to high water stress, and that share could rise to two-thirds by 2025 (WRI, 1998). Since 1940 the amount of freshwater used by humans has roughly quadrupled as the world population has doubled (Population Action International, 1997). Another doubling of the world population by 2100 cannot be ruled out. Assuming an upper limit of usable renewable freshwater of 9,000–14,000 cubic kilometres a year, a second quadrupling of world water use appears highly improbable.

In connection with the physical constraints to the use of water for power generation listed above, it should be noted that electricity generation—unlike, say, irrigation and domestic and industrial uses—is a non-consumptive use of water. Under otherwise favourable conditions, such as irrigation at low altitudes, water can be used first to generate power and then for other purposes.

A physical factor needed to develop hydropower economically is the availability of a suitable head. This limitation does not apply to other water uses. This factor is critical in many water-rich but low-lying regions.

Environmental and social constraints. More than 400,000 cubic kilometres of land have been inundated by the construction of dams (Shiklomanov, 1993). These dams generate 2,600 terawatt-hours a year of electricity. Assuming that all flooded areas are used for hydroelectricity, the energy density is 62 megawatt-hours a hectare per year. But hydroelectric plants vary widely in this respect. Goodland (1996) reports on installed capacity, flooded land, and relocated persons for 34 hydroelectric plants, mostly in developing countries. These plants have an average energy density of 135 megawatt-hours a hectare per year. The most land-intensive of them yields 3.5 megawatt-hours a year per hectare of flooded land, but the least land-intensive yields 1.48 million megawatt-hours a year per hectare.

Eleven of the thirty-four plants yield more than 1,800 megawatt-hours a hectare per year (0.205 kilowatt-years per year), the standard for a fixed array photovoltaic plant in sunny areas (see below). Biomass from forests (15 oven dry tonnes a hectare per year) and from crop plantation (10,000 litres of ethanol a hectare per year using sugarcane) have energy densities of about 20 megawatt-hours a hectare per year. Thus hydroelectricity is land-intensive—more so than photovoltaics but less so than biomass plantations.

Hydroelectricity has sparked controversy when large dams with energy densities as low as 0.2 megawatt-hours a hectare per year require large-scale flooding and displace people. Some large dams involve the resettlement of more than 100,000 people (Goodland, 1997). Mandatory resettlement and the boom and bust effects of dam construction on local economies have become contentious social and environmental issues. In the past, resettlement was the responsibility of governments and public utilities involved in the project. Despite enormous financial expen-ditures and compensation packages, resettlement efforts have had modest success. If private utilities are to finance hydro projects, they will have to take responsibility for dealing with resettlement issues. National and international cooperation on the development of environmental best practices (such as through working groups on hydropower and the environment in partnership with nongovernmental organisations) may foster public acceptance of hydropower projects. For example, the World Commission on Dams, an independent international commission established in 1998, is reviewing the development effectiveness of large dams and developing internationally acceptable criteria for future decision-making on dams.

Biomass resources

The world derives about 11 percent of its energy from biomass (IEA, 1998b). In developing countries biomass is the most important energy source, accounting for about 35 percent of the total (WEC, 1994). (In the largest developing countries, China and India, biomass accounts for 19 percent and 42 percent of the primary energy supply mix.) But in the world's poorest countries, biomass accounts for up to 90 percent of the energy supply, mostly in traditional or non-commercial forms.[10] This explains why biomass is often perceived as a fuel of the past—one that will be left behind as countries industrialise and their technological base develops.

But biomass resources are abundant in most parts of the world, and various commercially available conversion technologies could transform current traditional and low-tech uses of biomass to modern energy. If dedicated energy crops and advanced conversion technologies are introduced extensively (see chapter 7), biomass could make a substantial contribution to the global energy mix by 2100. Although most biomass is used in traditional ways (as fuel for households and small industries) and not necessarily in a sustainable manner, modern industrial-scale biomass applications have increasingly become commercially available. In 1996 estimates of biomass consumption ranged from 33–55 exajoules (WEC, 1998; IEA, 1998a; Hall, 1997).

Sources

Biomass can be classified as plant biomass (woody, non-woody, processed waste, or processed fuel; table 5.13) or animal biomass. Most woody biomass is supplied by forestry plantations, natural forests, and natural woodlands. Non-woody biomass and processed waste are products or by-products of agroindustrial activities. Animal manure can be used as cooking fuel or as feedstock for biogas generation. Municipal solid waste is also considered a biomass resource.

The annual global primary production of biomatter totals 220 billion oven dry tonnes, or 4,500 exajoules. The theoretically harvestable bioenergy potential is estimated to be 2,900 exajoules, of which 270 exajoules could be considered technically available on a sustainable basis (Hall and Rosillo-Calle, 1998). Hall and Rao

(1994) conclude that the biomass challenge is not availability but sustainable management, conversion, and delivery to the market in the form of modern and affordable energy services. Biomass resources can be converted to chemical fuels or electricity through several routes (see chapter 7).

Two major studies have recently acknowledged the benefits of sustainably produced biomass energy in future energy scenarios. The first is by Shell International Petroleum Company (Shell, 1996), which assessed potential major new sources of energy after 2020, when renewable energies are expected to become competitive with fossil fuels. The Intergovernmental Panel on Climate Change (IPCC, 1996a) has considered a range of options for mitigating climate change, and increased use of biomass for energy features in all its scenarios.

The expected role of biomass in the future energy supply of industrialised countries is based on two main considerations:

- The development of competitive biomass production, collection, and conversion systems to create biomass-derived fuels that can substitute for fossil fuels in existing energy supply infrastructure without contributing to the build-up of greenhouse gases in the atmosphere. Intermittent renewables, such as wind and solar energy, are more challenging to fit into existing distribution and consumption schemes.
- The potential resource base is generally considered substantial given the existence of land not needed or unsuitable for food production, as well as agricultural food yields that continue to rise faster than population growth.

In developing countries an assessment of potential bioenergy development must first address issues ranging from land-use conflicts with food production to health and environmental problems.

Perceptions and problems

Biomass is often perceived as a fuel of the past because of its low efficiency, high pollution, and associations with poverty.

- Biomass is the fuel most closely associated with energy-related health problems in developing countries. Exposure to particulates from biomass or coal burning causes respiratory infections in children, and carbon monoxide is implicated in problems in pregnancy (see chapter 3).
- Biomass fuels are bulky and may have a high water content. Fuel quality may be unpredictable, and physical handling of the material can be challenging. But technologies for biomass fuel upgrading (into pellets or briquettes, for example) are advancing, and the development of dedicated energy crops will also improve fuel standardisation.
- For biomass to become a major fuel, energy crops and plantations will have to become a significant land-use category. Land requirements will depend on energy crop yields, water availability, and the efficiency of biomass conversion to usable fuels. Assuming a 45 percent conversion efficiency to electricity and yields of 15 oven dry tonnes a hectare per year, 2 square kilometres of plantation would be needed per megawatt of electricity of installed capacity running 4,000 hours a year.
- The energy balance is not always favourable. While woody biomass energy output is 10–30 times greater than the energy input, the issue is less clear for liquid fuels derived from biomass (Shapouri, Duffield, and Graboski, 1995). Nevertheless, the use of sugarcane as a source of ethanol yields a very positive balance and is responsible for a net abatement of 9 million tonnes of carbon a year in Brazil (Moreira and Goldemberg, 1999). With the promising development of enzymatic hydrolysis, cellulose can be transformed into ethanol with a very favourable energy balance (PCAST, 1997).
- Large-scale production of biomass can have considerable negative impacts on soil fertility, water and agrochemical use, leaching of nutrients, and biodiversity and landscape. The collection and transport of biomass will increase vehicle and infrastructure use and air-borne emissions.

Technical potential of biomass energy plantations

To estimate future technical biomass potentials, it is necessary to know:

- The amount of land available for biomass plantation.
- The regional distribution of this land and distances to consumption centres.
- The productivity of the land for biomass production, including water availability.
- The environmental implications of biomass production.

TABLE 5.13. TYPES AND EXAMPLES OF PLANT BIOMASS

Woody biomass	Non-woody biomass	Processed waste	Processed fuels
• Trees • Shrubs and scrub • Bushes such as coffee and tea • Sweepings from forest floor • Bamboo • Palms	• Energy crops such as sugarcane • Cereal straw • Cotton, cassava, tobacco stems and roots (partly woody) • Grass • Bananas, plantains, and the like • Soft stems such as pulses and potatoes • Swamp and water plants	• Cereal husks and cobs • Bagasse • Wastes from pineapple and other fruits • Nut shells, flesh, and the like • Plant oil cake • Sawmill wastes • Industrial wood bark and logging wastes • Black liquor from pulp mills • Municipal waste	• Charcoal (wood and residues) • Briquette/densified biomass • Methanol/ethanol (wood alcohol) • Plant oils from palm, rape, sunflower, and the like • Producer gas • Biogas

Source: Adapted from IEA, 1998a.

TABLE 5.14. CURRENT GLOBAL LAND-USE PATTERN

Cropland (arableland and permanent crops)		Forests and woodland		Permanent pastures		Other land		
						Total other land		Land with rainfed cultivation potential
Gha	% of total	Gha	% of total	Gha	% of total	Gha	% of total	Gha
1.5	11	4.2	21	3.4	26	4.0	31	1.6–1.8

Note: Gha stands for billions of hectares. Total land availability is 13.1 billion hectares. *Source: FAO, 1993, 1999; Fischer and Heilig, 1998; WRI, 1998.*

TABLE 5.15. PROJECTED BIOMASS ENERGY POTENTIAL, 2050 (BILLIONS OF HECTARES UNLESS OTHERWISE INDICATED)

1	2	3	4	5	6[a]	7[b]	7[c]
Region	Population in 2050 (billions)	Land with crop production potential in 1990	Cultivated land in 1990	Additional cultivated land required in 2050	Maximum additional area for biomass production	Maximum additional amount of energy from biomass (exajoules)	
Industrialised countries[d]	–	–	0.670	0.050	0.100	17	30
Latin America							
Central and Caribbean	0.286	0.087	0.037	0.015	0.035	6	11
South America	0.524	0.865	0.153	0.082	0.630	107	189
Africa							
East	0.698	0.251	0.063	0.068	0.120	20	36
Central	0.284	0.383	0.043	0.052	0.288	49	86
North	0.317	0.104	0.040	0.014	0.050	9	15
Southern	0.106	0.044	0.016	0.012	0.016	3	5
West	0.639	0.196	0.090	0.096	0.010	2	3
Asia (excl. China)							
Western	0.387	0.042	0.037	0.010	-0.005	0	0
South-central	2.521	0.200	0.205	0.021	-0.026	0	0
East	1.722	0.175	0.131	0.008	0.036	6	11
South-east	0.812	0.148	0.082	0.038	0.028	5	8
China	–	–	–	–	–	**2[e]**	**2[e]**
Total[f]	**8.296**	**2.495**	**0.897**	**0.416**	**1.28**	**226**	**396**
Global biomass energy potential						**276[g]**	**446[g]**

a. (6) = (3) – (4) – (5). b. (7) = (6) x 8.5 [oven dry tonnes a hectare per year] x 20 [GJ per oven dry tonne] based on higher heating value (18 GJ per oven dry tonne for lower heating value). The assumptions for biomass productivity may appear on the high side, but they represent technically achievable yields given dedicated research, development, and dissemination. c. (7) = (6) x 15 [oven dry tonnes a hectare per year] x 20 [GJ per oven dry tonne] based on higher heating value (18 GJ per oven dry tonne for lower heating value). d. OECD, Central and Eastern Europe, newly independent states of the former Soviet Union. e. Data are projected values from d'Apote (1998), not maximum estimates. f. Totals in (2), (3), (4), and (5) exclude industrialised countries. g. Includes 50 EJ of current biomass energy generation. *Source: Derived from Fischer and Heilig, 1998; d'Apote, 1998; Nakićenović, Grübler, and McDonald, 1998.*

- The technical and economic performance of conversion technologies and net energy balance.

Current land-use patterns are shown in table 5.14. Land use is split into cropland, forests and woodland, permanent pastures, and other land. 'Other land' includes uncultivated land, grassland not used for pasture, built-on areas, wastelands, wetlands, roads, barren land, and protected forests. Less than a half of this land (1.6–1.8 billion hectares) can be used for rainfed cultivation, including biomass production (FAO, 1993; Fischer and Heilig, 1998).

Because energy plantations will likely account for 80–100 percent of biomass supply, large-scale use of biomass may compete with land for agriculture and food production. But biomass production for energy purposes should not infringe on food production. By 2100 an additional 1,700 million hectares of land are expected to be needed for agriculture, while 690–1,350 million hectares of additional land would be needed to support biomass energy requirements under a high-growth biomass energy scenario. Hence land-use conflicts could arise.

Land availability. Considerable areas are potentially available for large-scale production of biomass. In tropical countries large areas of deforested and degraded lands could benefit from the establishment of bioenergy plantations. While the theoretical potential of biomass production is one order of magnitude larger than current global energy use, the technical and economic potentials are much smaller. Technical and economic potentials will be determined by numerous factors ranging from current uses of degraded land (which in developing countries is often used by the poor to graze livestock) and land productivity to the economic reach of the land with respect to centres of energy demand.

The United Nations Food and Agriculture Organization's "World Agriculture towards 2010 study (Alexandratos, 1995) assesses potential cropland resources in more than 90 developing countries. In 2025 developing countries will be using only 40 percent of their potential cropland, but with large regional variations. Asia (excluding China, for which data were unavailable) will have a deficit of 47 million hectares, but yields of most food crops are low, and there is great potential for improvement using better genetic strains and management techniques. Modern agricultural technologies have not reached many rural farmers and could boost yields by as much as 50 percent. Whether future productivity gains can avoid a food deficit remains to be seen. Africa currently only uses 20 percent of its potential cropland and would still have 75 percent remaining in 2025. Latin America, currently using only 15 percent of its potential cropland, would have 77 percent left in 2025—land capable of producing nearly eight times its present energy consumption.

Large areas of surplus agricultural land in North America and Europe could become significant biomass production areas. U.S. farmers are paid not to farm about 10 percent of their land, and in the European Union 15 percent of arable farmland can be set aside (amounting to 15–20 million hectares by 2010, and possibly more than 50 million hectares later in the 21st century). In addition to more than 30 million hectares of cropland already set aside in the United States to reduce production or conserve land, another 43 million hectares of cropland have high erosion rates. Another 43 million hectares have wetness problems that could be eased with a shift to perennial energy crops. The U.S. Department of Agriculture estimates that a further 60 million hectares may be idled over the next 25 years.

A projection of these parameters for 2050 is shown in table 5.15. The theoretical and technical potential for biomass energy is about ten times current use (445 exajoules relative to 45 exajoules) and close to current global primary energy use of 402 exajoules a year. But the extent to which this potential can be achieved will depend on numerous factors. These include the share of land allocated to other uses (for example, plantations for timber and pulp), actually achievable specific biomass productivity, technologies for converting biomass to convenient energy services, transport distances, water availability, biodiversity, and the need for fertilisers.

Water resources. The supply of freshwater may become a limiting factor for both food and bioenergy production. Several studies have addressed water issues related to agriculture (FAO, 1999; Fischer and Heilig, 1998; WRI, 1998; Seckler and others, 1998, Falkenmark, 1997). But water availability for biomass production has not been addressed in great detail. The common view is that "the food needs of the world's rapidly growing population will introduce severe problems, either because the rate of growth will be too rapid for the additional water mobilisation to be met, or because the overall water demands will grow unrealistically high so that they cannot be met" (Falkenmark, 1997, p. 74).

Current and projected water resources, by region, are shown in table 5.16. Two levels of water requirements can be used to estimate water sufficiency. The lowest level of sufficiency is generally considered to be 1,000 cubic metres per capita a year, while the availability of more than 2,000 cubic metres per capita a year makes for a small probability of water shortages (Seckler and others, 1998, Falkenmark, 1997). In addition, a recent study commissioned by the United Nations Commission on Sustainable Development (Raskin and others, 1997) puts the upper limit of sustainable water consumption at 40 percent of available resources.

Even without considering water requirements for biomass production, water shortages (supply below 2,000 cubic metres per capita a year) are possible for about half the world's population as early as 2025. Thus the water constraint for extended biomass production will likely be of importance, especially in the long term (see also the section on physical constraints to hydroelectricity expansion, above).

TABLE 5.16. SUFFICIENCY OF WATER RESOURCES, 1990 AND 2025

Region	Population in 1990 (millions)	Water resources per capita in 1990 (cubic metres)	Water resources per capita in 2025 (cubic metres)	Supply in 2025 as percentage of available water resources
North America	278	19,370	36,200	6,065
Latin America and Caribbean	433	30,920	200	533
Western Europe	459	10,604	47,700	1,178
Central and Eastern Europe	277	1,902	10,700	744
Former Soviet Union	428	4,561	36,700	4,981
Middle East and North Africa	n.a.	n.a.	0	6
Sub-Saharan Africa	n.a.	n.a.	< 100	1,465
Pacific Asia	405	11,463	5,100	10
South Asia	1,133	4,537	2,000	1,611
Centrally planned Asia	1,252	2,987	18,600	2,344
Pacific OECD	144	8,463	41,600	1,729
Total	**4,809**	**8,497**	**198,900**	**20,666**

n.a. Not available.

Source: Seckler and others, 1998.

TABLE 5.17. CURRENT AND FEASIBLE BIOMASS PRODUCTIVITY, ENERGY RATIOS, AND ENERGY YIELDS FOR VARIOUS CROPS AND CONDITIONS

Crop and conditions	Yield (dry tonnes a hectare per year)	Energy ratio	Net energy yield (gigajoules a hectare per year)
Short rotation crops (willow, hybrid poplar; United States, Europe)			
• Short term	10-12	10:1	180-200
• Longer term	12-15	20:1	220-260
Tropical plantations (such as eucalyptus)			
• No genetic improvement, fertiliser use, and irrigation	2-10	10:1	30-180
• Genetic improvement and fertiliser use	6-30	20:1	100-550
• Genetic improvement, fertiliser and water added	20-30		340-550
Miscanthus/switchgrass			
• Short term	10-12	12:1	180-200
• Longer term	12-15	20:1	220-260
Sugarcane (Brazil, Zambia)	15-20	18:1[a]	400-500
Wood (commercial forestry)	1- 4	20/30:1	30- 80
Sugar beet (northwest Europe)			
• Short term	10-16	10:1	30-100
• Longer term	16-21	20:1	140-200
Rapeseed (including straw yields; northwest Europe)			
• Short term	4- 7	4:1	50- 90
• Longer term	7-10	10:1	100-170

a. The value in Moreira and Goldemberg (1999)—7.9:1—includes spending on transportation and processing of sugarcane to the final product ethanol.

Source: Biewinga and. van der Bijl, 1996; Hall and Scrase, 1998; IEA, 1994; Kaltschmitt, Reinhardt, and Stelzer, 1996; de Jager, Faaij, and Troelstra, 1998; IPCC, 1996a; Ravindranath and Hall, 1996.

Energy balances and biomass productivity

The energy production per hectare of various crops depends on climatic, soil, and management conditions. Examples of net energy yields—output minus energy inputs for agricultural operations, fertiliser, harvest, and the like—are given in table 5.17. Generally, perennial crops (woody biomass such as willow, eucalyptus, hybrid poplar, miscanthus or switchgrass grasses, sugarcane) perform better than annual crops (which are planted and harvested each year; examples include sorghum and hemp). This is because perennial crops have lower inputs and thus lower production costs as well as lower ecological impacts. Different management situations—irrigation, fertiliser application, genetic plant improvements, or some combination of the three—can also increase biomass productivity, by a factor of up to 10.

In addition to production and harvesting, biomass requires transportation to a conversion facility. The energy used to transport biomass over land averages about 0.5 megajoules per tonne-kilometre, depending on infrastructure and vehicle type (Borjesson, 1996). This means that land transport of biomass can become a significant energy penalty for distances of more than 100 kilometres. But such a radius covers a surface of hundreds of thousands of hectares, and is sufficient to supply enough biomass for conversion facilities of hundreds of megawatts of thermal power.

Transporting biomass by sea is also an option. Sea transport from Latin America to Europe, for example, would require less than 10 percent of the energy input of the biomass (Agterberg and Faaij, 1998). International transport of biomass (or rather, energy forms derived from biomass) is feasible from an energy (and cost) point of view. Sea transport of biomass is already practised: large paper and pulp complexes import wood from all over the world.

Agricultural and forestry residues and municipal waste

Agricultural and forestry residues are the organic by-products from food, fibre, and forest-product industries. Hall and others (1993) estimate the energy contents of these residues at more than one-third of global commercial energy use, of which about 30 percent is recoverable. Limitations arise from the impracticality of recovering all residues and from the need to leave some residues at the site (for fertilisation, for example) to ensure sustainable production of the main product.

Forestry residues obtained from sound forest management do not deplete the resource base. Under sustainable management, trees are replanted, the forest is managed for regeneration to enhance its health and future productivity, or both steps are taken. Energy is just one of the many outputs of forests. One of the difficulties is accurately estimating the potential of residues that can be available for energy use on a national or regional scale.

Municipal solid waste and industrial residues are indirect parts of the biomass resource base. Industrialised countries generate 0.9–1.9 kilograms per capita of municipal solid waste every day. Energy contents range from 4–13 megajoules per kilogram (IPPC, 1996a). Johansson and others (1993) report heating values as high as 15.9 megajoules per kilogram in Canada and the United States. Waste incineration, thermochemical gasification, and biodigestion convert municipal solid waste into electricity, heat, or even gaseous and liquid fuels. Because landfill disposal of municipal solid waste in densely populated areas is increasingly constrained and associated with rising tipping fees, such energy conversion can be profitable. Separating and recycling non-combustible contents.

Municipal solid waste incineration requires tight air pollution abatement due to the generation of complex compounds, some of which—such as dioxins—are carcinogenic (WEC, 1994). Advanced pollution abatement equipment essentially eliminates harmful pollutant emissions (Chen, 1995).

Johansson and others (1993) project that in industrialised countries energy production from urban refuse will reach about 3 exajoules a year by 2025.[11] Data on municipal solid waste in developing countries could not be found, but with rising living standards these same as those in low-income OECD countries. Globally, this could double the potential energy supply from municipal solid waste to 6 exajoules.

In tropical countries large areas of deforested and degraded lands could benefit from the establishment of bioenergy plantations.

Environmental implications of biomass production

Forest energy plantations consist of intensively managed crops of predominantly coppiced hardwoods, grown on cutting cycles of three to five years and harvested solely for use as a source of energy. The site, local, regional, and global impacts of these crops need to be considered. For example, if short-rotation energy crops replace natural forests, the main negative effects include increased risks of erosion, sediment loading, soil compaction, soil organic matter depletion, and reduced long-term site productivity. Water pollution from intensively managed sites usually results from sediment loading, enhanced nutrient concentrations, and chemical residues from herbicides. In contrast, if short-rotation crops replace unused or degraded agricultural land, this reduces erosion, nutrient leaching, and so on.

Developing new crops is a slow and costly process involving many technical and non-technical obstacles (Rosillo-Calle and others, 1996). Farmers have been slow to adopt new crops because of the long-term (more than 15 years) commitment needed. But research and development in Sweden and the United Kingdom have found frost- and pest-resistant clones and generated high yields by using mixed-clone planting and other management practices (Hall and Scrase, 1998).

Soil and nutrients. The abundant use of fertilisers and manure in agriculture has led to considerable environmental problems in various regions. These problems include nitrification of groundwater, saturation of soils with phosphate (leading to eutrophication), and difficulties meeting drinking water standards. In addition, the application of phosphates has increased heavy metal flux to the soil.

The agricultural use of pesticides can affect the health of people as well as the quality of groundwater and surface water—and, consequently, plants and animals. Specific effects depend on the type of chemical, the quantities used, and the method of application. Experience with perennial crops (willow, poplar, eucalyptus) suggests that they meet strict environmental standards. Agrochemical applications per hectare are 5–20 times lower for perennial energy crops than for food crops like cereals (Hall, 1997).

Limited evidence on the soil effects of energy forestry indicates that our understanding of this area is still relatively poor. Current evidence indicates that, with proper practices, forest soil management need not negatively affect physical, chemical, and biological soil parameters. Soil organic matter can improve soil fertility, biology, and physical properties (such as bulk density and water relations).[12] Relative to arable agriculture, energy plantations can improve the physical properties of soil because heavy machinery is used less often and soil disturbances are fewer. Soil solution nitrate can also be significantly reduced in soils planted with fast-growing trees, as long as nitrogen fertilisers are applied in accordance with the nutrient demands of the trees.

Biological fertilisers may replace chemical nitrogen fertilisers in energy forestry and crops. Biological fertilisation may include:

- Direct planting of nitrogen-fixing woody species and interplanting with nitrogen-fixing trees or ley crops.
- Soil amendments with various forms of organic matter (sewage sludge, wastewater, contaminated groundwater, farmyard manure, green manure).
- Stimulation or introduction of rhizosphere micro-organisms that improve plant nutrient uptake.
- Biological fallow.

Overall, from a nutritional point of view, there is no reason to believe that energy forest plantations will have significant environmental and ecological impacts when proper management practices are applied (Ericson, 1994).

Erosion. Erosion is related to the cultivation of many annual crops in many regions and is a concern with woody energy crops during their establishment phase. Little field data are available for comparison with arable crops. One of the most crucial erosion issues relates to the additional soil stabilisation measures required during the establishment of energy plantations. Growing ground-cover vegetation strips between rows of trees can mitigate erosion as long as competition does not occur.

Changing land use from agricultural production to an energy forest plantation reduces precipitation excess (groundwater recharges) and nutrient leaching. Nitrogen leaching decreases with energy plantations because the standard nutrient supply and the use of animal slurries lead to good uptake efficiencies relative to agricultural production systems. Nitrogen uptake efficiency for arable crops is about 50 percent, for grass 60 percent, and for forest plantations about 75 percent. The losses in these systems are mainly due to leaching and de-nitrification (Rijtman and Vries, 1994).

Another concern relates to possible soil compaction caused by heavy harvesting machinery. But these effects tend to be small to moderate due to the infrequency of forest harvesting (Smith, 1995). Overall, these impacts can be significantly lower than for conventional agriculture. When harvesting peren-nials, soil erosion can be kept to an absolute minimum because the roots remain in the soil. In the United States millions of hectares covered by grasses that fall under the soil conservation programme could provide a promising biomass production area, since biomass production can be combined with soil protection. Another benefit of perennial crops relative to annual crops is that their extensive root system adds to the organic matter content of the soil. Generally, diseases (such as eels) are prevented and the soil gets a better structure.

Many of the environmental and ecological impacts noted thus far can be alleviated with compensating measures. Energy crops are generally more environmentally acceptable than intensive agriculture because chemical inputs are lower and the soil undergoes less disturbance and compaction.

Biodiversity and landscape. Biomass plantations may be criticised because the range of biological species they support is much narrower than is found in natural ecosystems, such as forests. While this is generally true, it is not always relevant. Where plantations are estab-lished on degraded or excess agricultural lands, the restored lands are likely to support a more diverse ecology than before. Moreover, degraded land areas are plentiful: in developing countries about 0.5 billion hectares of degraded land are available (Bekkering, 1992). In any case, it is desirable to restore such land surfaces for water retention, erosion prevention, and microclimate control.

A good plantation design—including set-aside areas for native plants and animals situated in the landscape in a natural way—can avoid problems normally associated with monocultures. The presence of natural predators (such as insects) can also prevent the outbreak of pests and diseases. Altogether, more research and insights on plantations are needed, taking into account local conditions, species, and cultural aspects.

Very little is known about managing large-scale energy forest plantations or even agricultural and forestry residues for energy use.

Environmentally motivated responses to biomass production

Management practices are a key factor in the sustainable production and use of biomass. Yet very little is known about managing large-scale energy forest plantations or even agricultural and forestry residues for energy use.[13] The potential adverse environmental effects of large-scale dedicated energy crops and forestry plantations have raised concerns. Considerable effort has gone into investigating these concerns, and much knowledge has been gained (see Tolbert, 1998 and Lowe and Smith, 1997).

As a result good practice guidelines are being developed for the production and use of biomass for energy in Austria, Sweden, the United Kingdom, and the United States, as well as across Europe. These guidelines focus on short-rotation coppice and recognise the central importance of site-specific factors and the breadth of social and environmental issues that should be taken into consideration. But given that residues may remain more widely used than energy crops for quite some time, guidelines are urgently needed on when it is appropriate to use residues for energy, what fraction can be used, and how potential environmental advantages can be maximised.

A key message of these guidelines is that site and crop selection must be made carefully, and the crop must be managed sensitively. Energy crops should not displace land uses of high agricultural and ecological value. Consideration needs to be given to the landscape and visibility, soil type, water use, vehicle access, nature conservation, pests and diseases, and public access (ETSU, 1996; Hall and Scrase, 1998). The guidelines also stress the importance of consulting with local people at the early planning stage, and of ongoing community involvement in the development stages. Issues such as changes to the landscape, increased traffic movements, or new employment opportunities in rural areas may prove very significant to local people.

TABLE 5.18 ANNUAL SOLAR ENERGY RECEIVED BY THE EARTH

Parameter	Energy
Solar energy intercepted by the Earth at ~1.37 kilowatts per square metre	5.5×10^6
Solar energy reflected by the atmosphere back to space at ~0.3 kilowatts per square metre)	1.6×10^6
Solar energy potentially usable at ~1.0 kilowatts per square metre	3.9×10^6
Ratio of potentially usable solar energy to current primary energy consumption (402 exajoules)	~9,000

Source: Author's calculations.

Economics

The production costs of plantation biomass are already favourable in some developing countries. Eucalyptus plantations in Brazil supply wood chips for $1.5–2.0 a gigajoule (Carpentieri, Larson, and Woods, 1993). Based on this commercial experience, Carpentieri, Larson, and Woods (1993) project future biomass (wood chip) production of 13 exajoules a year on 50 million hectares of land. Costs are much higher in industrialised countries (with top values of around $4 a gigajoule in parts of Europe). But in the longer run, by about 2020, better crops and production systems are expected to cut biomass production costs in the United States to $1.5–2.0 a gigajoule for substantial land surfaces (Graham and others, 1995; Turnure and others, 1995).

Biomass costs are influenced by yield, land rent, and labour costs. Thus increases in productivity are essential to reducing biomass production costs. Yields can be improved through crop development, production integration (multiproduct plantation), and mechanisation. Competition for land use should be avoided to minimise inflated land rental rates. Labour costs can be lowered through mechanisation.

Solar energy resources

Solar energy has immense theoretical potential. The amount of solar radiation intercepted by Earth is more than three orders of magnitude higher than annual global energy use (table 5.18). But for several reasons the actual potential of solar energy is somewhat lower:

- Time variation. The amount of solar energy available at a given point is subject to daily and seasonal variations. So, while the maximum solar flux at the surface is about 1 kilowatt per square meter, the annual average for a given point can be as low as

0.1–0.3 kilowatts per square meter, depending on location. For large-scale application of solar energy—more than 5–10 percent of the capacity of an integrated electricity system—the variability of insolation necessitates energy storage or backup systems to achieve a reliable energy supply.

- Geographic variation. The availability of solar energy also depends on latitude. Areas near the equator receive more solar radiation than subpolar regions. But geographic variation can be significantly reduced by using collectors capable of following the position of the sun. Polar regions show a notable increase in irradiance due to light reflection from snow.
- Weather conditions. Weather is another, even stronger, factor influencing the availability of solar energy. Annual average sky clearness may vary by 80–90 percent in locations such as Khartoum (Sudan), Dakar (Bangladesh), Kuwait, Baghdad (Iraq), Salt Lake City (Utah), and by 40–50 percent in Tokyo (Japan) and Bonn (Germany; WEC, 1994). Solar irradiance is often quite diffuse, leading to lower average power densities. Thus large-scale generation of solar energy can require significant land.
- Siting options. While building structures provide interesting local siting possibilities,[14] large-scale solar collectors can be located on land that is not being used—which amounts to about 4 billion hectares (FAO, 1999). Assuming 10 percent of this unused land is allocated for habitation (cities, towns, villages) and infrastructure (roads, ports, railways), some 3.6 billion hectares are available for solar energy.

Large-scale availability of solar energy will thus depend on a region's geographic position, typical weather conditions, and land availability. Using rough estimates of these factors, solar energy potential is shown in table 5.19. This assessment is made in terms of primary energy—that is, energy before the conversion to secondary or final energy is estimated. The amount of final energy will depend on the efficiency of the conversion device used (such as the photovoltaic cell applied). Issues related to energy conversion and its impact on the amount of energy delivered are considered in chapter 7.

This assessment also reflects the physical potential of solar energy. Thus it does not take into account possible technological, economic, and social constraints on the penetration of solar energy except for two different assumptions on available land. The consideration of such constraints is likely to result in much lower estimates—as in WEC (1994), where global solar energy potential in 2020 ranges from 5–230 exajoules a year.

The solar energy potential in table 5.19 is more than sufficient to meet current and projected energy uses well beyond 2100. Thus the contribution of solar energy to global energy supplies will not be limited by resource availability. Rather, three factors will determine the extent to which solar energy is used in the longer run: the availability of efficient and low-cost technologies to convert solar energy into electricity and eventually hydrogen, of effective energy storage technologies for electricity and hydrogen, and of high-efficiency end-use technologies fuelled by electricity and hydrogen.

TABLE 5.19. ANNUAL SOLAR ENERGY POTENTIAL (EXAJOULES)

Region	Minimum	Maximum
North America	181.1	7,410
Latin America and Caribbean	112.6	3,385
Western Europe	25.1	914
Central and Eastern Europe	4.5	154
Former Soviet Union	199.3	8,655
Middle East and North Africa	412.4	11,060
Sub-Saharan Africa	371.9	9,528
Pacific Asia	41.0	994
South Asia	38.8	1,339
Centrally planned Asia	115.5	4,135
Pacific OECD	72.6	2,263
Total	**1,575.0**	**49,837**
Ratio to current primary energy consumption (402 exajoules)	**3.9**	**124**
Ratio to projected primary energy consumption in 2050 (590–1,050 exajoules)	**2.7–1.5**	**84–47**
Ratio to the projected primary energy consumption in 2100 (880–1,900 exajoules)	**1.8–0.8**	**57–26**

Note: The minimum and maximum reflect different assumptions on annual clear sky irradiance, annual average sky clearance, and available land area. *Source: IEA, 1998c; Nakićenović, Grübler, and McDonald, 1998.*

Wind energy resources

Winds develop when solar radiation reaches the Earth's highly varied surface unevenly, creating temperature, density, and pressure differences. Tropical regions have a net gain of heat due to solar radiation, while polar regions are subject to a net loss. This means that the Earth's atmosphere has to circulate to transport heat from the tropics towards the poles. The Earth's rotation further contributes to semi-permanent, planetary-scale circulation patterns in the atmosphere. Topographical features and local temperature gradients also alter wind energy distribution.

A region's mean wind speed and its frequency distribution have to be taken into account to calculate the amount of electricity that can be produced by wind turbines. Wind resources can be exploited in areas where wind power density is at least 400 watts per square metre at 30 metres above the ground (or 500 watts per square metre at 50 metres). Moreover, technical advances are expected to open new areas to development. The following assessment includes regions where the average annual wind power density exceeds 250–300 watts per square metre at 50 metres—corresponding to class 3 or higher in the widely used U.S. classification of wind resources.

TABLE 5.20. ANNUAL WIND ENERGY POTENTIAL

Region	Percentage of land area	Population density (people per square kilometre)	Gross electric potential (thousands of terawatt-hours)	Assessed wind energy potential (exajoules)	Estimated second-order potential (thousands of terawatt-hours)	Assessed wind energy potential, (exajoules)
Africa	24	20	106	1,272	10.6	127
Australia	17	2	30	360	3	36
North America	35	15	139	1,670	14	168
Latin America	18	15	54	648	5.4	65
Western Europe	42	102	31	377	4.8	58
Eastern Europe and former Soviet Union	29	13	106	1,272	10.6	127
Asia (excl. former Soviet Union)	9	100	32	384	4.9	59
Total	**23**		**500**	**6,000**	**53**	**640**

Note: Refers to wind energy with average annual power density of more than 250–300 watts per square metre at 50 metres (resources class 3 and higher in the U.S. classification of wind resources). The energy equivalent in exajoules is calculated based on the electricity generation potential of the referenced sources by dividing the electricity generation potential by a factor of 0.3 (a representative value for the efficiency of wind turbines, including transmission losses), resulting in a primary energy estimate. Totals are rounded.

Source: Grubb and Meyer, 1993.

TABLE 5.21. ESTIMATED ANNUAL WIND ENERGY RESOURCES

Region	Land surface with wind class 3–7		Wind energy resources without land restriction		Wind energy resources if less than 4 percent of land is used	
	Percent	Thousands of square kilometres	Thousands of terawatt-hours	Exajoules	Thousands of terawatt-hours	Exajoules
North America	41	7,876	126	1,512	5.0	60
Latin America and Caribbean	18	3,310	53	636	2.1	25
Western Europe	42	1,968	31	372	1.3	16
Eastern Europe and former Soviet Union	29	6,783	109	1,308	4.3	52
Middle East and North Africa	32	2,566	41	492	1.6	19
Sub-Saharan Africa	30	2,209	35	420	1.4	17
Pacific Asia	20	4,188	67	804	2.7	32
China	11	1,056	17	204	0.7	8
Central and South Asia	6	243	4	48	0.2	2
Total[a]	**27**	**30,200**	**483**	**5,800**	**18.7**	**231**

Note: The energy equivalent in exajoules is calculated based on the electricity generation potential of the referenced sources by dividing the electricity generation potential by a factor of 0.3 (a representative value for the efficiency of wind turbines, including transmission losses), resulting in a primary energy estimate.
a. Excludes China.

Source: WEC, 1994.

Several studies have analysed the global potential of power production using wind. To define technical wind power potential, one needs take into account siting constraints. First-order exclusions may include definite constraints such as cities, forests, difficult terrain, and inaccessible mountain areas. The most important limitations arise from social, environmental, and land-use constraints, including visual and noise impacts, all of which depend on political and social judgements and traditions and may vary by region. Regional estimates of wind electricity potentials (class 3 and above) are summarised in table 5.20.

Grubb and Meyer (1993) estimate the theoretical electricity generation potential of global wind energy resources (class 3 and above) to be 500,000 terawatt-hours a year (see table 5.20). Only about 10 percent of this theoretical potential may be realistically harvested.

WEC (1994) places the global theoretical wind potential at 483,000 terawatt-hours a year (table 5.21). This estimate is based on the assumption that 27 percent of the Earth's land surface is exposed to an annual mean wind speed higher than 5.1 metres per second at 10 metres above ground (class 3 and above), and that this entire area could be used for wind farms. WEC also suggests a more conservative estimate of 19,000 terawatt-hours a year, assuming for practical reasons that just 4 percent of the area exposed to this wind speed can be used for wind farms. (The 4 percent estimate comes from detailed studies of wind power potential in the Netherlands and the United States.)

Geothermal energy resources

Geothermal energy is generally defined as heat stored within the Earth. The Earth's temperature increases by about 3 degrees Celsius for every 100 metres in depth, though this value is highly variable. Heat originates from the Earth's molten interior and from the decay of radioactive materials.

Four types of geothermal energy are usually distinguished:

- Hydrothermal—hot water or steam at moderate depths (100–4,500 metres).
- Geopressed—hot-water aquifers containing dissolved methane under high pressure at depths of 3–6 kilometres.
- Hot dry rock—abnormally hot geologic formations with little or no water.
- Magma—molten rock at temperatures of 700–1,200 degrees Celsius.

Today only hydrothermal resources are used on a commercial scale for electricity generation (some 44 terawatt-hours of electricity in 1997) and as a direct heat source (38 terawatt-hours of heat; Björnsson and others, 1998).

The global potential of geothermal energy is on the order of 140,000,000·exajoules. But a much smaller amount can be classified as resources and reserves (table 5.22). Still, geothermal energy has enormous potential. Even the most accessible part, classified as reserves (about 434 exajoules), exceeds current annual consumption of primary energy. But like other renewable resources (solar energy, wind energy), geothermal energy is widely dispersed. Thus the technological ability to use geothermal energy, not its quantity, will determine its future share. The regional distribution of geothermal energy potential is shown in table 5.23.

Environmental aspects of geothermal energy use relate primarily to gas admixtures to the geothermal fluids such as carbon dioxide, nitrogen, hydrogen sulphides or ammonia and heavy metals such as mercury. The quantities vary considerably with location and temperatures of the feed fluid but are generally low compared to those associated with fossil fuel use. Because the chemicals are dissolved in the feed water which is usually re-injected into the drill holes, releases are minimal.

Ocean energy resources

Four types of ocean energy are known:

- Tidal energy—energy transferred to oceans from the Earth's rotation through gravity of the sun and moon.
- Wave energy—mechanical energy from wind retained by waves.
- Ocean thermal energy—energy stored in warm surface waters that can be made available using the temperature difference with water in ocean depths.
- Salt gradient energy—the energy coming from salinity differences between freshwater discharges into oceans and ocean water.

Tidal energy is the most advanced in terms of current use, with a

TABLE 5.22. ANNUAL GEOTHERMAL POTENTIAL (EXAJOULES)

Resource category	Energy
Accessible resource base (amount of heat that could theoretically be tapped within a depth of 5 kilometres)	140,000,000
Useful accessible resource base	600,000
Resources (portion of the accessible resource base expected to become economical within 40–50 years)	5,000
Reserves (portion of the accessible resource base expected to become economical within 10–20 years)	500

Source: Palmerini, 1993; Björnsson and others, 1998.

TABLE 5.23. ANNUAL GEOTHERMAL POTENTIAL BY REGION (EXAJOULES)

Resource category	Energy
North America	26,000,000 •(18.9)
Latin America and Caribbean	26,000,000 •(18.6)
Western Europe	7,000,000 • (5.0)
Eastern Europe and former Soviet Union	23,000,000 •(16.7)
Middle East and North Africa	6,000,000 • (4.5)
Sub-Saharan Africa	17,000,000 •(11.9)
Pacific Asia (excl. China)	11,000,000 • (8.1)
China	11,000,000 • (7.8)
Central and South Asia	13,000,000 • (9.4)
Total	**140,000,000**

Note: Numbers in parentheses are shares of world total.

Source: WEC, 1994; EPRI, 1978.

TABLE 5.24. ANNUAL OCEAN ENERGY POTENTIAL		
Resource category	**Terawatt-hours**	**Exajoules**
Tidal energy	22,000	79
Wave energy	18,000	65
Ocean thermal energy[a]	2,000,000	7,200
Salt gradient energy[b]	23,000	83
Total	**2,063,000**	**7,400**

a. The potential of ocean thermal energy is difficult to assess but is known to be much larger than for the other types of ocean energy. The estimate used here assumes that the potential for ocean thermal energy is two orders of magnitude higher than for tidal, wave, or salt gradient energy. b. Assumes the use of all the world's rivers with devices of perfect efficiency. *Source: WEC, 1994, 1998; Cavanagh, Clarke, and Price, 1993.*

number of commercial plants in operation. Despite notable progress in recent years, the other ocean energy resources are generally not considered mature enough for commercial applications.

The theoretical potential of each type of ocean energy is quite large (table 5.24). But like other renewables, these energy resources are diffuse, which makes it difficult to use the energy. The difficulties are specific to each type of ocean energy, so technical approaches and progress differ as well.

Conclusion

Globally, energy resources are plentiful and are unlikely to constrain sustainable development even beyond the 21st century (tables 5.25 and 5.26). If historical observations are any indication, possible intergenerational equity conflicts on resource availability and costs will most likely be equilibrated by technological progress. The fossil resource base is at least 600 times current fossil fuel use, or 16 times cumulative fossil fuel consumption between 1860 and 1998. (The resource base does not include methane clathrates and other oil, gas, and coal occurrences, the inclusion of which could quadruple the resource base.)

While the availability and costs of fossil fuels are unlikely to impede sustainable development, current practices for their use and waste disposal are not sustainable (UNCED, 1993). In their natural states, energy resources are environmentally inert (from the perspective of sustainable development). Even mining and production of fossil resources interfere little with sustainable development relative to current pollution emissions and wastes associated with their combustion for the provision of energy services. Thus the economic and environmental performance of fossil, nuclear, and renewable conversion technologies—from resource extraction to waste disposal—will determine the extent to which an energy resource can be considered sustainable.

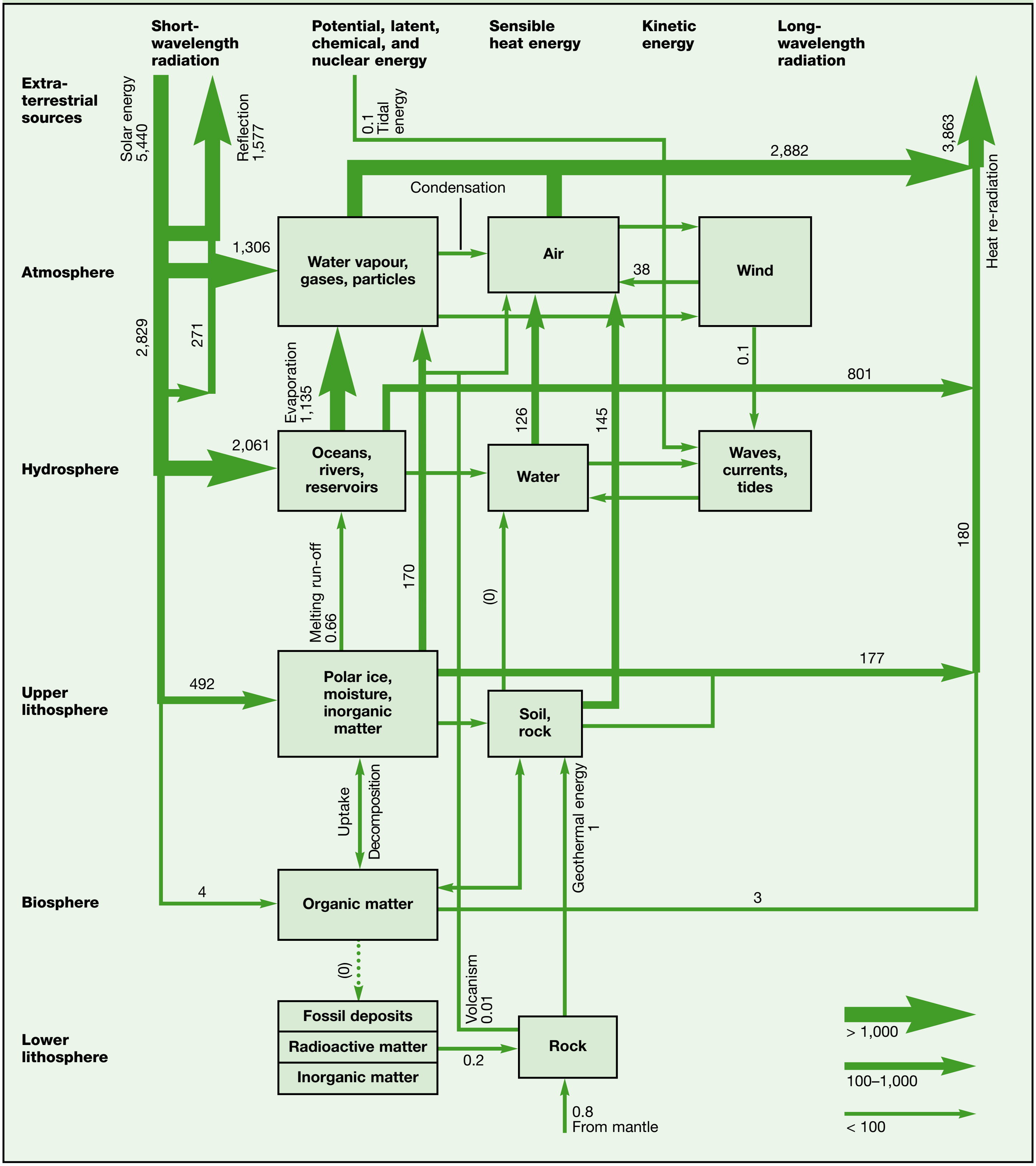
Relative economic and environmental aspects make up the demand pull for the development of future energy resources. Socio-political preferences and policies can appreciably amplify or weaken the demand pull. In many countries, especially transition economies but also several energy-exporting developing countries, the domestic fossil energy resource endowment has yet to be evaluated using market-based criteria. Such evaluations may lead to a substantial revision of readily available reserve volumes and point to unforeseen investments in up-stream operations to raise productivity to international standards.

Energy resources are not evenly distributed across the globe. Although renewables are more evenly distributed and accessible

TABLE 5.25. SUMMARY OF GLOBAL FOSSILE AND FISSILE RESOURSES (THOUSANDS OF EXAJOULES)						
Resource	**Consumed by end 1998**	**Consumed in 1998**	**Reserves**	**Resources**	**Resource base[a]**	**Additional occurrences**
Oil	5.14	0.14	11.11	21.31	32.42	45
Conventional	4.85	0.13	6.00	6.07	12.08	
Unconventional	0.29	0.01	5.11	15.24	20.35	45
Gas	2.38	0.08	14.88	34.93	49.81	930
Conventional	2.35	0.08	5.45	11.11	16.57	
Unconventional	0.03	0.00	9.42	23.81	33.24	930
Coal	5.99	0.09	20.67	179.00	199.67	
Fossile total	**13.51**	**0.32**	**46.66**	**235.24**	**281.89**	**975**
Uranium						
Open cycle in thermal reactors[b]	n.e.	0.04	1.89	3.52	5.41	7.1[c]
Closed cycle with fast reactors[d]	—	—	113	211	325	426[b]
Fossile and fissile total[e]	**n.e.**	**0.36**	**48**	**446**	**575**	**1,400**

n.e. Not estimated. — Negligible.
a. Sum of reserves and resources. b. Calculated from the amount in tonnes of uranium, assuming 1 tonne = 589 terajoules (IPCC, 1996a). c. Does not include uranium from seawater or other fissile materials. d. Calculated assuming a 60-fold increase relative to the open cycle, with 1 tonne = 35,340 terajoules. e. All totals are rounded. *Source: Author's calculations from previous chapter tables.*

FIGURE 5.4. GLOBAL ENERGY BALANCE AND FLOWS WITHOUT ANTHROPOGENIC INTERFERENCE



Note: Energy flows are in thousands of exajoules a year. Numbers in parentheses are uncertain or rounded.

Source: Sørensen, 1979.

Renewable energy flows are three orders of magnitude larger than current global energy use.

than fossil and nuclear resources, their economic potential is affected by land-use constraints, variation of availability as a function of latitude (solar power) and location (wind power and hydroelectricity), solar irradiation, and water and soil quality (biomass). Still, renewable energy flows are three orders of magnitude larger than current global energy use (figure 5.4). Their use will depend primarily on the commercialisation of conversion technologies. Similarly, uranium and thorium resources are plentiful and do not pose a constraint to the long-term deployment of nuclear power.

Most long-term energy demand and supply scenarios involve increasing global energy trade, irrespective of the underlying assumptions of energy resource and technology development. Supply security considerations may tilt the balance in favour of one energy resource or set of resources. Supply security improves with the share of energy supplies from national sources. A thorough evaluation of a nation's energy resource endowment based on market criteria is an important step towards supply security.

The world energy system's current dependence on fossil fuel conversion is considered unsustainable by the United Nations (UNDP, 1997). It has often been assumed that fossil resource limitations or the "running out of resources" phenomenon (Meadows and others, 1972) would wean the energy system off fossil sources and bring about the necessary course correction towards sustainable energy development. Based on long-term global energy demand expectations, current understanding of the world's fossil resource endowment, and production economics, this is unlikely to happen before the end of the 21st century. Thus a transition to sustainable energy systems that continue to rely predominantly on fossil fuels will depend on the development and commercialisation of fossil technologies that do not close their fuel cycle through the atmosphere.[15] Alternatively, the transition will likely require determined policies to move away from fossil fuels. Large increases in fossil fuel prices as a result of rapid resource depletion are unlikely to drive the transition.

Transitions motivated by factors other than short-term economics usually invoke extra costs that have to be borne by contemporary societies for the benefit of future ones. In either case—making the use of fossil fuels sustainable or shifting to non-fossil energy sources—society must first recognise that the current energy system is unsustainable and that adequate policy measures need to be introduced. These measures may stimulate technological advances and development, change consumer preferences, or both. After all, the existence of enormous fossil, nuclear, and renewable resources is irrelevant unless there is a demand for them and unless technologies for their extraction and sustainable conversion to energy services are commercially available. Otherwise, resources remain 'neutral stuff'. ■

TABLE 5.26. SUMMARY OF THE RENEWABLE RESOURCE BASE (EXAJOULES A YEAR)

Resource	Current use[a]	Technical potential	Theoretical potential
Hydropower	9	50	147
Biomass energy	50	> 276	2,900
Solar energy	0.1	> 1,575	3,900,000
Wind energy	0.12	640	6,000
Geothermal energy	0.6	5,000	140,000,000
Ocean energy	n.e.	n.e.	7,400
Total	**56**	**> 7,600**	**> 144,000,000**

n.e. Not estimated.
a. The electricity part of current use is converted to primary energy with an average factor of 0.385. *Source: Author's calculations from previous chapter tables.*

Notes

1. However, Masters and others argue that most major oil-producing countries are reporting as proven reserves what the authors would define as identified reserves (proven plus probable plus possible).

2. Oil production costs and market prices may differ significantly, however. Oil is a highly political commodity with market prices that often have little relation to costs. While economic rationality suggests that the least-cost oil reserves are produced first, this has not been the case, at least since 1973. That gives low-cost and lowest-cost producers quite a bit of leverage in engineering market price instabilities or backing out of high-cost production.

3. The ratio of reserves to production assumes constant demand for a resource as well as constant production over the period suggested by the ratio. In essence, it implies that production will plummet from full output in one year to zero output in another. In reality, production peaks and then declines along a quasi-logistic curve, and supplies will last much longer, though at much lower volumes than suggested by the ratio.

4. Once an investment has been committed for gas export pipelines, it cannot easily be designated for other uses (whereas an oil tanker may be rerouted instantly by a single radio call). Disputes between trading partners may put the investment at risk and lead to disruptions in supply and offtake.

5. Temperature increases as a function of high atmospheric carbon concentrations are highly uncertain. For example, the mean global temperature increase estimated for a doubling of carbon dioxide concentrations ranges from 1.5–4.5 Kelvin (IPCC, 1996b).

6. Uranium reserves as defined by the Uranium Institute are proven and probable reserves (labelled Reserve Class I) at production costs of less than $40 a kilogram, less than $60 a kilogram, and less than $80 a kilogram. WEC (1998) uses the term *proven reserves* for the NEA-IAEA category reasonably assure resources.

7. The Uranium Institute uses for the lesser-known category Reserve Class II. WEC (1998) defines its estimated additional amounts recoverable to correspond to NEA-IAEA EAR I.

8. A detailed and consistent compilation for all countries is not available, and country-specific information is often published without verification. *The International Water Power and Dams Construction Yearbook* (1998) and even the *World Atlas and Industry Guide* (1998) present a few inconsistencies. Nevertheless, a cross-check showed a similar world total for these two sources.

9. The consideration of social and environmental aspects suggests that this is the market potential. Because of inconsistencies in the definitions used in different appraisals, here the notion of economic potential is maintained.

10. Non-commercial biomass is difficult to account for accurately or goes unreported. For instance, biomass data for China and India are not included in the WEC statistics.

11. It is assumed that 75 percent of the energy in urban refuse can be recovered and that the waste generation rate per capita is constant over time. Estimates for Canada and the United States are based on a per capita waste generation rate of 330 kilograms a year and a heating value of 15.9 megajoules per kilogram (and a 50 percent recycling rate). Estimates for other OECD countries are based on a per capita waste generation rate of 300 kilograms a year and a heating value of 12.7 megajoules per kilogram.

12. A review of the literature indicates that over time there are few, if any, long-term losses of soil carbon after forest harvesting and reforestation. But substantial losses of soil carbon are reported for systems involving harvesting followed by intensive burning or mechanical site damage. Holistic, life-cycle approaches are required to estimate the contribution of intensive forest management and bioenergy systems to local and global carbon balances.

13. There are exceptions: a lot is known about eucalyptus for charcoal production and sugarcane for ethanol production in Brazil (which tend to follow traditional agricultural and forestry practices). Similarly, there is extensive knowledge about willows for heat power generation in Sweden, where the cultivation of about 16,000 hectares has also borrowed considerably from traditional forestry and agricultural activities.

14. For example, if the performance and costs of solar collectors integrated with buildings are improved, commercial buildings could become local energy production centres. Such integration would enlarge the space available for solar collection and allow buildings to contribute to their energy use.

15. Decarbonisation of fuels (before use) or greenhouse gas abatement (after fuel production or use) and subsequent carbon dioxide disposal could eventually avoid closing the carbon fuel cycle through the atmosphere (see chapters 8 and 11).

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