renewable energy technologies

CHAPTER 7

Wim C. Turkenburg (Netherlands)

LEAD AUTHORS: Jos Beurskens (Netherlands), André Faaij (Netherlands), Peter Fraenkel (United Kingdom), Ingvar Fridleifsson (Iceland), Erik Lysen (Netherlands), David Mills (Australia), Jose Roberto Moreira (Brazil), Lars J. Nilsson (Sweden), Anton Schaap (Netherlands), and Wim C. Sinke (Netherlands)

CONTRIBUTING AUTHORS: Per Dannemand Andersen (Denmark), Sheila Bailey (United States), Jakob Björnsson (Iceland), Teun Bokhoven (Netherlands), Lex Bosselaar (Netherlands), Suani Teixeira Coelho (Brazil), Baldur Eliasson (Switzerland), Brian Erb (Canada), David Hall (United Kingdom), Peter Helby (Sweden), Stephen Karekezi (Kenya), Eric Larson (United States), Joachim Luther (Germany), Birger Madson (Denmark), E.V.R. Sastry (India), Yohji Uchiyama (Japan), and Richard van den Broek (Netherlands)

ABSTRACT

In 1998 renewable energy sources supplied 56 ± 10 exajoules, or about 14 percent of world primary energy consumption. The supply was dominated by traditional biomass (38 ± 10 exajoules a year). Other major contributions came from large hydropower (9 exajoules a year) and from modern biomass (7 exajoules). The contribution of all other renewables—small hydropower, geothermal, wind, solar, and marine energy—was about 2 exajoules. That means that the energy supply from new renewables was about 9 exajoules (about 2 percent of world consumption). The commercial primary energy supply from renewable sources was 27 ± 6 exajoules (nearly 7 percent of world consumption), with 16 ± 6 exajoules from biomass.

Renewable energy sources can meet many times the present world energy demand, so their potential is enormous. They can enhance diversity in energy supply markets, secure long-term sustainable energy supplies, and reduce local and global atmospheric emissions. They can also provide commercially attractive options to meet specific needs for energy services (particularly in developing countries and rural areas), create new employment opportunities, and offer possibilities for local manufacturing of equipment.

There are many renewable technologies. Although often commercially available, most are still at an early stage of development and not technically mature. They demand continuing research, development, and demonstration efforts. In addition, few renewable energy technologies can compete with conventional fuels on cost, except in some niche markets. But substantial cost reductions can be achieved for most renewables, closing gaps and making them more competitive. That will require further technology development and market deployment—and boosting production capacities to mass production.

For the long term and under very favourable conditions, the lowest cost to produce electricity might be \$0.01–0.02 a kilowatt-hour for geothermal, \$0.03 a kilowatt-hour for wind and hydro, \$0.04 a kilowatt-hour for solar thermal and biomass, and \$0.05–0.06 a kilowatt-hour for photovoltaics and marine currents. The lowest cost to produce heat might be \$0.005 a kilowatt-hour for geothermal, \$0.01 a kilowatt-hour for biomass, and \$0.02–0.03 a kilowatt-hour for solar thermal. The lowest cost to produce fuels might be \$1.5 a gigajoule for biomass, \$6–7 a gigajoule for ethanol, \$7–10 a gigajoule for methanol, and \$6–8 a gigajoule for hydrogen.

Scenarios investigating the potential of renewables reveal that they might contribute 20–50 percent of energy supplies in the second half of the 21st century. A transition to renewables-based energy systems would have to rely on:

- Successful development and diffusion of renewable energy technologies that become more competitive through cost reductions from technological and organisational developments.
- Political will to internalise environmental costs and other externalities that permanently increase fossil fuel prices.

Many countries have found ways to promote renewables. As renewable energy activities grow and require more funding, the tendency in many countries is to move away from methods that let taxpayers carry the burden of promoting renewables, towards economic and regulatory methods that let energy consumers carry the burden. ■

Many renewables technologies are suited to small off-grid applications, good for rural, remote areas, where energy is often crucial in human development.

Renewable energy sources have been important for humans since the beginning of civilisation. For centuries and in many ways, biomass has been used for heating, cooking, steam raising, and power generation—and hydropower and wind energy, for movement and later for electricity production. Renewable energy sources generally depend on energy flows through the Earth's ecosystem from the insolation of the sun and the geothermal energy of the Earth. One can distinguish:

- Biomass energy (plant growth driven by solar radiation).
- Wind energy (moving air masses driven by solar energy).
- Direct use of solar energy (as for heating and electricity production).
- Hydropower.
- Marine energy (such as wave energy, marine current energy, and energy from tidal barrages).
- Geothermal energy (from heat stored in rock by the natural heat flow of the Earth).

If applied in a modern way, renewable energy sources (or renewables) are considered highly responsive to overall energy policy guidelines and environmental, social, and economic goals:

- Diversifying energy carriers for the production of heat, fuels, and electricity.
- Improving access to clean energy sources.
- Balancing the use of fossil fuels, saving them for other applications and for future generations.
- Increasing the flexibility of power systems as electricity demand changes.
- Reducing pollution and emissions from conventional energy systems.
- Reducing dependency and minimising spending on imported fuels.

Furthermore, many renewables technologies are suited to small off-grid applications, good for rural, remote areas, where energy is often crucial in human development. At the same time, such small energy systems can contribute to the local economy and create local jobs.

The natural energy flows through the Earth's ecosystem are immense, and the theoretical potential of what they can produce for human needs exceeds current energy consumption by many times. For example, solar power plants on 1 percent of the world's desert area would generate the world's entire electricity demand today.

TABLE 7.1. CATEGORIES OF RENEWABLE ENERGY CONVERSION TECHNOLOGIES

Technology	Energy product	Application
Biomass energy		
Combustion (domestic scale)	Heat (cooking, space heating)	Widely applied; improved technologies available
Combustion (industrial scale)	Process heat, steam, electricity	Widely applied; potential for improvement
Gasification/power production	Electricity, heat (CHP).	Demonstration phase
Gasification/fuel production	Hydrocarbons, methanol, H_2	Development phase
Hydrolysis and fermentation	Ethanol	Commercially applied for sugar/ starch crops; production from wood under development
Pyrolysis/production of liquid fuels	Bio-oils	Pilot phase; some technical barriers
Pyrolysis/production of solid fuels	Charcoal	Widely applied; wide range of efficiencies
Extraction	Biodiesel	Applied; relatively expensive
Digestion	Biogas	Commercially applied
Wind energy		
Water pumping and battery charging	Movement, power	Small wind machines, widely applied
Onshore wind turbines	Electricity	Widely applied commercially
Offshore wind turbines	Electricity	Development and demonstration phase
Solar energy		
Photovoltaic solar energy conversion	Electricity	Widely applied; rather expensive; further development needed
Solar thermal electricity	Heat, steam, electricity	Demonstrated; further development needed
Low-temperature solar energy use	Heat (water and space heating, cooking, drying) and cold	Solar collectors commercially applied; solar cookers widely applied in some regions; solar drying demonstrated and applied
Passive solar energy use	Heat, cold, light, ventilation	Demonstrations and applications; no active parts
Artificial photosynthesis	H_2 or hydrogen rich fuels	Fundamental and applied research
Hydropower	Power, electricity	Commercially applied; small and large scale applications
Geothermal energy	Heat, steam, electricity	Commercially applied
Marine energy		
Tidal energy	Electricity	Applied; relatively expensive
Wave energy	Electricity	Research, development, and demonstration phase
Current energy	Electricity	Research and development phase
Ocean thermal energy conversion	Heat, electricity	Research, development, and demonstration phase
Salinity gradient / osmotic energy	Electricity	Theoretical option
Marine biomass production	Fuels	Research and development phase

BOX 7.1. LAND USE REQUIREMENTS FOR ENERGY PRODUCTION

Biomass production requires land. The productivity of a perennial crop (willow, eucalyptus, switchgrass) is 8–12 tonnes of dry matter per hectare a year. The lower heating value (LHV) of dry clean wood amounts to about 18 gigajoules a tonne; the higher heating value about 20 gigajoules a tonne. Thus 1 hectare can produce 140–220 gigajoules per hectare a year (LHV; gross energy yield; taking into account energy inputs for cultivation, fertiliser, harvest, and so on, of about 5 percent in total). The production of 1 petajoule currently requires 4,500–7,000 hectares. To fuel a baseload biomass energy power plant of 600 megawatts of electricity with a conversion efficiency of 40 percent would require 140,000–230,000 hectares. Annual production of 100 exajoules (one-quarter of the world's current energy use) would take 450–700 million hectares.

With ample resources and technologies at hand for renewable energy use, the question of future development boils down to economic and political competitiveness with other energy sources. Since the performance and costs of conversion technologies largely determine the competitiveness of renewables, technological development is the key. Still, the World Energy Council, Shell, the Intergovernmental Panel on Climate Change (IPCC), and several UN bodies project a growing role for renewable energy in the 21st century with major contributions from biomass, hydropower, wind, and solar.

A wide variety of technologies are available or under development to provide inexpensive, reliable, and sustainable energy services from renewables (table 7.1). But the stage of development and the competitiveness of those technologies differ greatly. Moreover, performance and competitiveness are determined by local conditions, physical and socioeconomic, and on the local availability of fossil fuels.

All renewable energy sources can be converted to electricity. Since some major renewable energy sources are intermittent (wind, solar), fitting such supplies into a grid creates challenges. This is less of a problem for biomass, hydropower, and geothermal. Only a few of them produce liquid and gaseous fuels as well as heat directly.

Biomass energy

Biomass is a rather simple term for all organic material that stems from plants (including algae), trees, and crops. Biomass sources are therefore diverse, including organic waste streams, agricultural and forestry residues, as well as crops grown to produce heat, fuels, and electricity *(*energy plantations*)*.

Biomass contributes significantly to the world's energy supply—probably accounting for 45 ± 10 exajoules a year (9–13 percent of the world's energy supply; IEA, 1998; WEC, 1998; Hall, 1997). Its largest contribution to energy consumption—on average between a third and a fifth—is found in developing countries. Compare that with 3 percent in industrialised countries (Hall and others, 1993; WEC, 1994b; IEA REWP, 1999).

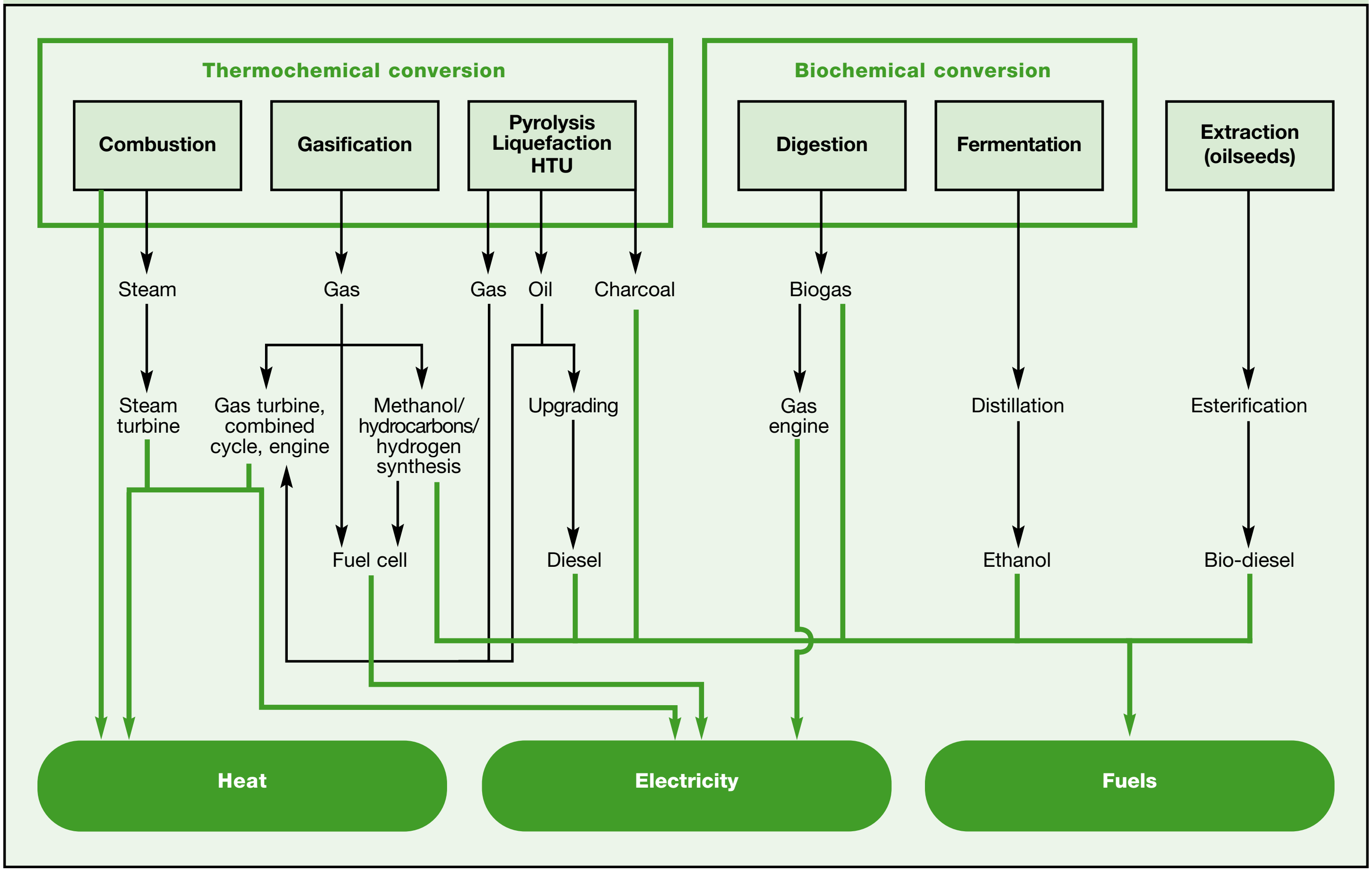
Dominating the traditional use of biomass, particularly in developing countries, is firewood for cooking and heating. Some traditional use is not sustainable because it may deprive local soils of needed nutrients, cause indoor and outdoor air pollution, and result in poor health. It may also contribute to greenhouse gas emissions and affect ecosystems (chapters 3 and 10). The modern use of biomass, to produce electricity, steam, and biofuels, is estimated at 7 exajoules a year. This is considered fully commercial, based on bought biomass or used for productive purposes. That leaves the traditional at 38 ± 10 exajoules a year. Part of this is commercial—the household fuelwood in industrialised countries and charcoal and firewood in urban and industrial areas in developing countries. But there are almost no data on the size of this market. If it can be estimated at between 10 percent and 30 percent (9 ± 6 exajoules a year), which seems probable, the total commercial use of biomass in 1998 was 16 ± 6 exajoules.

Since the early 1990s biomass has gained considerable interest world-wide. It is carbon neutral when produced sustainably. Its geographic distribution is relatively even. It has the potential to produce modern energy carriers that are clean and convenient to use. It can make a large contribution to rural development. And its

TABLE 7.2. POTENTIAL CONTRIBUTION OF BIOMASS TO THE WORLD'S ENERGY NEEDS

Source	Time frame (year)	Total projected global energy demand (exajoules a year)	Contribution of biomass to energy demand (exajoules a year)	Comments
RIGES (Johansson and others, 1993)	2025 2050	395 561	145 206	Based on calculation with the RIGES model
SHELL (Kassler,1994)	2060	1,500 900	220 200	Sustained growth scenario Dematerialization scenario
WEC (1994a)	2050 2100	671–1,057 895–1,880	94–157 132–215	Range given here reflects the outcomes of three scenarios
Greenpeace and SEI (Lazarus and others,1993)	2050 2100	610 986	114 181	A scenario in which fossil fuels are phased out during the 21st century
IPCC (Ishitani and Johansson,1996)	2050 2100	560 710	280 325	Biomass intensive energy system development

FIGURE 7.1. MAIN BIOMASS ENERGY CONVERSION ROUTES



attractive costs make it a promising energy source in many regions. With various technologies available to convert biomass into modern energy carriers, the application of commercial and modern biomass energy systems is growing in many countries.

The potential of biomass energy

The resource potential of biomass energy is much larger than current world energy consumption (chapter 5). But given the low conversion efficiency of solar to biomass energy (less than 1 percent), large areas are needed to produce modern energy carriers in substantial amounts (box 7.1). With agriculture modernised up to reasonable standards in various regions, and given the need to preserve and improve the world's natural areas, 700–1,400 million hectares may be available for biomass energy production well into the 21st century (Hall and others, 1993; Larson and others, 1995; Ishitani and others, 1996; IIASA and WEC, 1998; Larson, Williams, and Johansson, 1999). This includes degraded, unproductive lands and excess agricultural lands. The availability of land for energy plantations strongly depends on the food supplies needed and on the possibilities for intensifying agricultural production in a sustainable way.

A number of studies have assessed the potential contribution of biomass to the world energy supply (table 7.2). Although the percentage contribution of biomass varies considerably, especially depending on expected land availability and future energy demand, the absolute potential contribution of biomass in the long term is high—from 100–300 exajoules a year. World-wide annual primary energy consumption is now about 400 exajoules.

Biomass energy conversion technologies

Conversion routes to produce heat, electricity, and/or fuels from biomass are plentiful (figure 7.1).

Production of heat. In developing countries the development and introduction of improved stoves for cooking and heating can have a big impact on biomass use (chapters 3 and 10). Especially in colder climates (Scandinavia, Austria, Germany) domestic biomass-fired heating systems are widespread. Improved heating systems are automated, have catalytic gas cleaning, and use standard fuel (such as pellets). The benefit over open fireplaces is considerable, with advanced domestic heaters obtaining efficiencies of more than 70 percent and producing far fewer atmospheric emissions. The present heat-generating capacity is estimated to be more than 200 gigawatts of thermal energy.

Production of electricity. Some features of the main thermochemcial biomass energy conversion routes to electricity and combined heat and power (CHP) are presented in table 7.3. Combustion of biomass to produce electricity is applied commercially in many regions, with the total installed capacity estimated at 40 gigawatts of electricity. The application of fluid bed combustion and advanced gas cleaning allows for efficient production of electricity (and heat) from biomass. At a scale of 20–100 megawatts of electricity, electrical efficiencies of 20–40 percent are possible (van den Broek and others, 1996; Solantausta and others, 1996). Often the electricity is produced along with heat or steam (CHP) in Denmark and Sweden. In Southeast Asia, through the Association of Southeast Asian Nations–European Union COGEN Programme, sawmill factories in Indonesia, Malaysia, and Thailand have cogeneration systems, using wood-waste from the factories.

Co-combustion systems—combining, say, natural gas and coal with biomass—are built in such places as Denmark with the benefits of greater economies of scale and reduced fuel supply risks. Co-combustion of biomass in coal-fired power plants is a popular way to increase biomass-based power generation capacity with minimal investment (chapter 8). Other advantages over coal-based power production are the higher efficiencies (due in most cases to the large scale of the existing power plant) and lower sulphur dioxide (SO_2) and nitrogen oxide (NO_x) emissions (Meuleman and Faaij, 1999).

Large gasification. Gasification technologies can convert biomass into fuel gas, cleaned before its combustion in, say, a gas turbine. Biomass integrated gasification/combined cycle (BIG/CC) systems combine flexible fuel characteristics and high electrical efficiency. Electrical conversion efficiencies of 40 percent (LHV) are possible at a scale of about 30 megawatts of electricity (Consonni and Larson, 1994a, b; Faaij and others, 1997).

Demonstration projects are under way in various countries and for various gasification concepts. In Brazil a project supported by the World Bank and Global Environment Facility will demonstrate a 30 megawatts-electric BIG/CC unit fired with cultivated eucalyptus (Elliott and Booth, 1993). Sweden's first BIG/CC unit, based on pressurised gasification, has several thousands of hours of operational experience. Three other demonstration units around the 6–10 megawatts-electric scale are under way. An atmospheric BIG/CC system is being commissioned in Yorkshire, United Kingdom. In the United States an indirect gasification process is under demonstration at the Burlington power station.

The first generation of BIG/CC systems shows high unit capital costs. Depending on the scale, prices are $2,800–5,000 a kilowatt of electricity. But cost reduction potential is considerable for BIG/CC systems—capital costs might come down to $1,100–2,000 a kilowatt (Williams, 1996; Solantausta and others, 1996; Faaij, Meuleman, and Van Ree, 1998). Co-gasification of biomass, another option, is being applied in the United States and Europe. An interesting alternative for fuel gas produced through biomass gasification is its use in existing (or new) natural gas-fired combined cycles. In this way, economies of scale come with a safe fuel supply (Walter and others, 1998). This option has not been demonstrated yet, but more research is under way.

Small gasification. Small (fixed bed) gasifiers coupled to diesel or gasoline engines (typically for systems of 100–200 kilowatts of electricity with an approximate electrical efficiency of 15–25 percent) are commercially available on the market. But high costs and the need for gas cleaning and careful operation have blocked application in large numbers. Some systems are being applied fairly successfully in rural India and in China and Indonesia (Kaltschmitt and others, 1998; Stassen, 1995).

Biogas production. Anaerobic digestion of biomass has been demonstrated and applied commercially with success in many situations and for a variety of feedstocks–such as organic domestic waste, organic industrial wastes, manure, and sludges. Large advanced systems are developed for wet industrial waste streams and applied in many countries. In India there is widespread production of biogas from

TABLE 7.3. MAIN THERMOCHEMICAL BIOMASS ENERGY CONVERSION ROUTES TO HEAT AND ELECTRICITY

Conversion system	Range	Net efficiency (percent, LHV)	Investment cost (dollars a kilowatt of electricity)
Combustion			
Combined heat and power (CHP)	100 kWe to 1 MWe	60–90 (overall)	
	1–10 MWe	80–99 (overall)	
Standalone	20–100 MWe	20–40 (electrical)	1,600–2,500
Co-combustion	5–20 MWe	30–40 (electrical)	250 plus costs of existing power plant
Gasification			
CHP			900–3,000 (depending on location and configuration)
Diesel	100 kWe to 1 MWe	15–25 (electrical)	
Gas turbine	1–10 MWe	25–30 (electrical)	
BIG/CC	30–100 MWe	40–55 (electrical)	1,100–2,000 (when commercially proven)
Digestion			
Wet biomass materials	Up to several MWe	10–15 (electrical)	5,000

Biomass has gained considerable interest world-wide. It is carbon neutral when produced sustainably.

animal and other wastes for cooking, lighting, and power generation (chapter 10).

Digestion has a low overall electric conversion efficiency (roughly 10–15 percent, depending on the feedstock) and is particularly suited for wet biomass materials. Landfills contribute to atmospheric methane emissions. In many situations the collection of landfill gas and its conversion to electricity using gas engines is profitable, and such systems are becoming more widespread (Faaij, Hekkert, and others, 1998).

Production of liquid and gaseous fuels from biomass (bio-oil and biocrude). At temperatures around 500 degrees Celsius in the absence of oxygen, pyrolysis converts biomass to liquid (bio-oil), gaseous, and solid (charcoal) fractions. With flash pyrolysis techniques (fast pyrolysis) the liquid fraction can be up to 70 percent of the thermal biomass input. Bio-oil contains about 40 weight-percent of oxygen and is corrosive and acidic. The oil can be upgraded to reduce the oxygen content, but that has economic and energy penalties. Pyrolysis and upgrading technology are still largely in the pilot phase (Bridgewater, 1998).

Hydrothermal upgrading (HTU), originally developed by Shell, converts biomass at a high pressure and at moderate temperatures in water to biocrude. Biocrude contains far less oxygen than bio-oil produced through pyrolysis, but the process is still in a pre-pilot phase (Naber and others 1997).

Ethanol. Production of ethanol by fermenting sugars is a classic conversion route for sugar cane, maize, and corn on a large scale, especially in Brazil, France, and the United States. Zimbabwe also has a considerable fuel ethanol programme using sugar cane (Hemstock and Hall, 1995). The U.S. and European programmes convert surplus food crops to a useful (by) product. But ethanol production from maize and corn is far from being competitive with gasoline and diesel. Nor is the overall energy balance of such systems very favourable.

An exception is Brazil's PRO-ALCOOL programme, due to the high productivity of sugar cane (Rosillo-Calle and Cortez, 1998). This programme is discussed in some detail later in this chapter. In 1998 world production of ethanol was estimated at 18 billion litres (equivalent to 420 petajoules).

Ethanol can also be produced by the hydrolysis of lignocellulosic biomass, a potentially low-cost and efficient option. Hydrolysis techniques are gaining more development attention, particularly in Sweden and the United States, but some fundamental issues need to be resolved. If these barriers are lowered and ethanol production is combined with efficient electricity production from unconverted wood fractions (such as lignine), ethanol costs could come close to current gasoline prices—as low as $0.12 a litre at biomass costs of about $2 a gigajoule (Lynd, 1996). Overall system conversion efficiency could go up to about 70 percent (LHV).

Esters from oilseeds. Oilseeds, such as rapeseed, can be extracted and converted to esters and are well suited to replace diesel. Substantial quantities of RME (rape methyl esters) are produced in the European Union and to a lesser extent in North America. But RME requires substantial subsidies to compete with diesel. Energy balances for RME systems are less favourable than those for perennial crops (Ishitani and Johansson, 1996), so the net energy production per hectare is low. These balances can be improved if by-products (such as straw) are also used as an energy source.

Methanol, hydrogen, and hydrocarbons through gasification. Production of methanol and hydrogen using gasification technology and traditional syngas conversion processes could offer an attractive conversion route for biomass over the long term. Although such concepts received serious attention in the early 1980s, low oil prices made them unattractive. New technology—such as liquid phase methanol production (combined with electricity generation) and new gas separation technology—offers lower production costs and higher overall conversion efficiencies. With large-scale conversion and the production of both fuel and electricity, methanol and hydrogen from lignocellulosic biomass might compete with gasoline and diesel (Spath and others, 2000; Faaij and others, 1999). In addition, synthetic hydrocarbons and methanol can be produced from syngas using Fischer-Tropsch synthesis (Larson and Jin, 1999a, b).

Environmental impacts of biomass energy systems

Biomass energy can be carbon neutral when all biomass produced is used for energy (short carbon cycle). But sustained production on the same surface of land can have considerable negative impacts on soil fertility, water use, agrochemical use, biodiversity, and landscape. Furthermore, the collection and transport of biomass increases the use of vehicles and infrastructure and the emissions to the atmosphere (Tolbert, 1998; Borjesson, 1999; Faaij, Meuleman, and others, 1998). Seen world-wide, climatic, soil, and socioeconomic conditions set strongly variable demands for what biomass production will be sustainable.

Erosion. Erosion is a problem related to the cultivation of many annual crops in many regions. The best-suited energy crops are perennials, with much better land cover than food crops. And during harvest, the removal of soil can be kept to a minimum, since the roots remain in the soil. Another positive effect is that the formation of an extensive root system adds to the organic matter content of the soil. Generally, diseases (such as eelworms) are prevented, and the soil structure is improved.

Water use. Increased water use caused by additional demands of (new) vegetation can become a concern, particularly in arid and semi-arid regions. The choice of crop can have a considerable effect on water-use efficiency. Some eucalyptus species have a very good water-use efficiency, considering the amount of water needed per tonne of biomass produced. But a eucalyptus plantation on a large area could increase the local demand for groundwater and affect its level. On the other hand, improved land cover generally is good for water retention and microclimatic conditions. Thus the impacts on the hydrological situation should be evaluated at the local level.

Agrochemicals. Pesticides affect the quality of groundwater and surface water and thus plants and animals. Specific effects depend on the type of chemical, the quantity used, and the method of application. Experience with perennial crops (willow, poplar, eucalyptus, miscanthus) suggests that they meet strict environmental standards. Compared with food crops like cereals, application rates of agrochemicals per hectare are a fifth to a twentieth for perennial energy crops (Faaij, Meuleman, and others, 1998; Borjesson, 1999).

Nutrients. The abundant use of fertilisers and manure in agriculture has led to considerable environmental problems in various regions: nitrification of groundwater, saturation of soils with phosphate, eutrophication, and unpotable water. Phosphates have also increased the heavy metal flux of the soil. But energy farming with short rotation forestry and perennial grasses requires less fertiliser than conventional agriculture (Kaltschmitt and others, 1996). With perennials, better recycling of nutrients is obtained. The leaching of nitrogen for willow cultivation can be a half to a tenth that for food crops, meeting stringent standards for groundwater protection. The use of plantation biomass will result in removal of nutrients from the soil that have to be replenished in one way or the other. Recycling of ashes is feasible for returning crucial trace elements and phosphates to the soil, already common practice in Austria and Sweden. In Brazil stillage, a nutrient rich remainder of sugar cane fermentation, is returned to sugar cane plantations.

Biodiversity and landscape. Biomass plantations can be criticised because the range of biological species they support is much narrower than what natural forests support (Beyea and others, 1991). Although this is generally true, it is not always relevant. It would be if a virgin forest is replaced by a biomass plantation. But if plantations are established on degraded lands or on excess agricultural lands, the restored lands are likely to support a more diverse ecology.

Degraded lands are plentiful: estimates indicate that about 2 billion hectares of degraded land are 'available' in developing countries (Larson, Williams, and Johansson, 1999; IIASA and WEC, 1998). It would be desirable to restore such land surfaces anyway—for water retention, erosion prevention, and (micro-) climate control. A good plantation design, including areas set aside for native plants and animals fitting in the landscape in a natural way, can avoid the problems normally associated with monocultures, acknowledging that a plantation of energy crops does not always mean a monoculture.

Other risks (fire, disease). Landscaping and managing biomass production systems can considerably reduce the risks of fire and disease. Thus they deserve more attention in coming projects, policies, and research.

Conversion and end use. Conversion of biomass to desired intermediate energy carriers and their use for energy services should meet strict environmental standards as well. Problems that could occur (such as emissions to air) can be easily countered with technology that is well understood and available. Clean combustion of biomass is now common practice in Scandinavia. Gasification allows for cleaning fuel gas prior to combustion or further processing. Care should be paid to small (less than 1 megawatts of thermal energy) conversion systems: technology to meet strict emission standards is available but can have a serious impact on the investment and operational costs of such small systems (Kaltschmitt and others, 1998; Stassen, 1995).

Economics of biomass energy systems

Biomass is a profitable alternative mainly when cheap or even negative-cost biomass residues or wastes are available. To make biomass

TABLE 7.4. MAIN PERFORMANCE DATA FOR SOME CONVERSION ROUTES OF BIOMASS TO FUELS

	RME	Ethanol from sugar or starch crops	Ethanol from lignocellulosic biomass	Hydrogen from lignocellulosic biomass	Methanol from lignocellulosic biomass	Bio-oil from lignocellulosic biomass
Concept	Extraction and esterification	Fermentation	Hydrolysis, fermentation, and electricity production	Gasification	Gasification	Flash pyrolysis
Net energy efficiency of conversion	75 percent based on all energy inputs	50 percent for sugar beet; 44 percent for sugar cane	60–70 percent (longer term with power generation included)	55–65 percent 60–70 percent (longer term)	50–60 percent 60–70 percent (longer term)	70 percent (raw bio-oil)
Cost range, short term[a]	$15–25 a gigajoule (northwest Europe)	$15–25 a gigajoule for sugar beet; $8–10 a gigajoule for sugar cane	$10–15 a gigajoule	$8–10 a gigajoule	$11–13 a gigajoule	n.a.
Cost range, long term[a]	n.a.	n.a.	$6–7 a gigajoule	$6–8 a gigajoule	$7–10 a gigajoule	Unclear

a. Diesel and gasoline production costs vary widely depending on the oil price. Longer–term projections give estimates of roughly $0.25–0.35 a litre, or $8–11 a gigajoule. Retail fuel transport prices are usually dominated by taxes of $0.50–1.30 a litre depending on the country.

Source: Wyman and others, 1993; IEA, 1994; Williams and others, 1995; Jager and others, 1998; Faaij, Hamelinck, and Agterberg, forthcoming.

competitive with fossil fuels, the production of biomass, the conversion technologies, and total bio-energy systems require further optimisation.

Biomass production. Plantation biomass costs already are favourable in some developing countries. Eucalyptus plantations in northeast Brazil supply wood chips at prices between $1.5–2.0 a gigajoule (Carpentieri and others, 1993). Costs are (much) higher in industrialised countries, such as $4 a gigajoule in parts of northwest Europe (Rijk, 1994; van den Broek and others, 1997). But by about 2020, with improved crops and production systems, biomass production costs in the United States could be about $1.5–2.0 a gigajoule for substantial land surfaces (Graham and others, 1995; Turnure and others, 1995; Hughes and Wiltsee, 1995). It is expected for large areas in the world that low-cost biomass can be produced in large quantities. Its competitiveness will depend on the prices of coal (and natural gas), but also on the costs and net returns from alternative, competing uses of productive land.

Power generation from biomass. With biomass prices of about $2 a gigajoule, state of the art combustion technology at a scale of 40–60 megawatts of electricity can result in electricity production costs of $0.05–0.06 a kilowatt-hour (USDOE, 1998b; Solantausta and others, 1996). Co-combustion, particularly at efficient coal-fired power plants, can obtain similar costs. If BIG/CC technology becomes available commercially, production costs could drop further to about $0.04 a kilowatt-hour, especially with higher electrical efficiencies. For larger scales (more than 100 megawatts of electricity) it is expected that cultivated biomass will compete with fossil fuels in many situations. The benefits of lower specific capital costs and increased efficiency certainly outweigh the increase in costs and energy use for transport for considerable distances if a reasonably well-developed infrastructure is in place (Marrison and Larson, 1995a, b; Faaij, Hamelinck, and Agterberg, forthcoming).

Decentralised power (and heat) production is generally more expensive and therefore is better suited for off-grid applications. The costs of gasifier/diesel systems are still unclear and depend on what emissions and fuel quality are considered acceptable. Combined heat and power generation is generally economically attractive when heat is required with a high load factor.

Production of liquid and gaseous fuels from biomass. The economies of 'traditional' fuels like RME and ethanol from starch and sugar crops in moderate climate zones are poor and unlikely to reach competitive price levels. Methanol, hydrogen, and ethanol from lignocellulosic biomass offer better potential in the longer term (table 7.4).

Implementation issues

Modern use of biomass is important in the energy systems of a number of countries (table 7.5). Other countries can be mentioned as well—as in Asia, where biomass, mainly traditional biomass, can account for 50–90 percent of total energy. India has installed more than 2.9 million biomass digesters in villages and produces biogas for cooking—and is using small gasifier diesel systems for rural electrification. Biomass power projects with an aggregate capacity of 222 megawatts have been commissioned in India, with another 280 megawatts under construction (MNCES, 1999). And with tens of millions of hectares of degraded soil, India is involved in wood-for-energy production schemes. Throughout Southeast Asia the interest in modern bio-energy applications has increased in recent years, partly because of the fast-growing demand for power

TABLE 7.5. BIOMASS IN THE ENERGY SYSTEMS OF SELECTED COUNTRIES

Country	Role of biomass in the energy system
Austria	Modern biomass accounts for 11 percent of the national energy supply. Forest residues are used for (district) heating, largely in systems of a relatively small scale.
Brazil	Biomass accounts for about a third of the energy supply. Main modern applications are ethanol for vehicles produced from sugar cane (13–14 billion litres a year) and substantial use of charcoal in steel industry. Government supports ethanol. PRO-ALCOOL is moving towards a rationalisation programme to increase efficiency and lower costs.
Denmark	A programme is under way to use 1.2 million tonnes of straw as well as use forest residues. Various concepts have been devised for co-firing biomass in larger-scale combined heating and power plants, district heating, and digestion of biomass residues.
Finland	Twenty percent of its primary energy demand comes from modern biomass. The pulp and paper industry makes a large contribution through efficient residue and black liquor use for energy production. The government supports biomass; a doubling of the contribution is possible with available resources.
Sweden	Modern biomass accounts for 17 percent of national energy demand. Use of residues in the pulp and paper industry and district heating (CHP) and use of wood for space heating are dominant. Biomass is projected to contribute 40 percent to the national energy supply in 2020.
United States	About 10,700 megawatts-electric biomass-fired capacity was installed by 1998; largely forest residues. Four billion litres per year of ethanol are produced.
Zimbabwe	Forty million litres of ethanol are produced a year. Biomass satisfies about 75 percent of national energy demand.

Source: Kaltschmitt and others, 1998; Rosillo-Calle and others, 1996; Rosillo and Cortez, 1998; NUTEK, 1996; USDOE, 1998a; Hemstock and Hall, 1995.

and because biomass residues from various agricultural production systems are plentiful (box 7.2; Lefevre and others, 1997).

Some 700–1,400 million hectares may be available for biomass energy production well into the 21st century.

Barriers. Bio-energy use varies remarkably among countries. Varying resource potentials and population densities are not the only reasons. Other barriers hamper implementation:

- *Uncompetitive costs.* The main barrier is that the energy carriers are not competitive unless cheap or negative cost biomass wastes and residues are used. Technology development could reduce the costs of bio-energy. In Denmark and Sweden, where carbon and energy taxes have been introduced, more expensive wood fuels and straw are now used on a large scale. But world-wide, the commercial production of energy crops is almost non-existent. (Brazil is a major exception, having introduced subsidies to make ethanol from sugar cane competitive with gasoline.)
- *The need for efficient, cheap, environmentally sound energy conversion technologies.* Strongly related to costs issues are the availability and the full-scale demonstration of advanced conversion technology, combining a high energy conversion efficiency and environmentally sound performance with low investment costs. Biomass integrated gasifier/combined cycle (BIG/CC) technology can attain higher conversion efficiency at lower costs. Further development of gasification technologies is also important for a cheaper production of methanol and hydrogen from biomass.
- *Required development of dedicated fuel supply systems.* Experience with dedicated fuel supply systems based on 'new' energy crops, such as perennial grasses, is very limited. Higher yields, greater pest resistance, better management techniques, reduced inputs, and further development of machinery are all needed to lower costs and raise productivity. The same is true for harvesting, storage, and logistics.
- *Specific biomass characteristics.* The solar energy conversion efficiency of biomass production is low—in practice less than 1 percent. So, fairly large land surfaces are required to produce a substantially amount of energy. Moreover, biomass has a low energy density. Compare coal's energy density of 28 gigajoules a tonne, mineral oil's 42 gigajoules a tonne, and liquefied natural gas's 52 gigajoules a tonne with biomass's 8 gigajoules a tonne of wood (at 50 percent moisture content). Transport is thus an essential element of biomass energy systems, and transportation distances can become a limiting factor. Another complication is that biomass production is usually bound to seasons, challenging the supply and logistics of a total system. And varying weather conditions affect production year-to-year.
- *Socioeconomic and organisational barriers.* The production of crops based on perennial grasses or short rotation forestry differs substantially from that of conventional food crops. Annual crops provide farmers with a constant cash flow for each hectare of land. For short rotation coppice, however, the intervals between harvests can be 2–10 years, restricting the flexibility of farmers to shift from one crop to another. In addition, bio-energy systems require complex organisations and many actors, creating non-technical barriers.
- *Public acceptability.* Since biomass energy systems require substantial land areas if they are to contribute much to the total energy supply, the needed changes in land-use, crops, and landscape might incite public resistance. And to be acceptable to most people, the ecological impacts of biomass production systems have to be minimal. Increased traffic in biomass production areas might also be seen as a negative.
- *Ecological aspects.* Not much is known about the effects of large-scale energy farming on landscapes and biodiversity. Energy crop plantations have to fit into the landscape both ecologically and aesthetically. And in addition to minimising the environmental impact, attention should be paid to fitting biomass production into existing agricultural systems.
- *Competition for land use.* Competition for land or various land claims may turn out to be a limitation in various regions. Opinions differ on how much (agricultural) land will become available for energy crops (Dyson, 1996; Brown and others, 1996; Gardner, 1996). An accepted principle is that biomass production for energy should not conflict with food production. But given the large potential to increase the productivity of conventional agriculture (Luyten, 1995; WRR, 1992; Larson, Williams, and Johansson, 1999), land's availability is not necessarily a barrier. If conventional agriculture has higher productivity, it will become more profitable—so bio-energy will face even stiffer competition from conventional crops than it does today.

BOX 7.2. INDUSTRIAL USES OF BIO-ENERGY

Two large industrial sectors offer excellent opportunities to use biomass resources efficiently and competitively world-wide: paper and pulp, and sugar (particularly using sugar cane as feed). Traditionally, these sectors use biomass residues (wood waste and bagasse) for their internal energy needs, usually inefficient conversions to low-pressure steam and some power. The absence of regulations to ensure reasonable electricity tariffs for independent power producers make it unattractive for industries to invest in more efficient power generation. But the liberalisation of energy markets in many countries is removing this barrier, opening a window to reduce production costs and modernise production capacity.

Efficient boilers have been installed in many production facilities. Gasification technology could offer even further efficiency gains and lower costs—say, when applied for converting black liquor (Larson and others, 1998). The power generated is generally competitive with grid prices. In Nicaragua electricity production from bagasse using improved boilers could meet the national demand for electricity (van den Broek and van Wijk, 1998).

Strategies. Six areas are essential for successful development and implementation of sustainable and economically competitive bio-energy systems: technologies, production, markets, polygeneration, externalities, and policy.

Technological development and demonstration of key conversion technologies. Research, demonstration, and commercialisation of advanced power generation technology are essential—especially for BIG/CC technology, which can offer high conversion efficiencies, low emissions, and low costs. Another interesting route is producing modern biofuels, using hydrolysis and gasification. Combining biomass with fossil fuels can be an excellent way to achieve economies of scale and reduce the risks of supply disruptions.

More experience with and improvement of biomass production. Local assessments are needed to identify optimal biomass production systems, and more practical experience is needed with a wide variety of systems and crops. Certainly, more research and testing are needed to monitor the impact of energy crops, with particular attention to water use, pest abatement, nutrient leaching, soil quality, biodiversity (on various levels), and proper landscaping. Perennial crops (grasses) and short rotation coppice (eucalyptus, willow) can be applied with minimal ecological impacts.

Cost reduction is essential, though several countries already obtain biomass production costs below $2 a gigajoule. Larger plantations, improved species, and better production systems and equipment can reduce costs further. Another promising way to lower costs is to combine biomass production for energy with other (agricultural or forest) products (multi-output production systems). Yet another is to seek other benefits from biomass production—preventing erosion, removing soil contaminants, and creating recreational and buffer zones.

Creating markets for biomass production, trade, and use. At local and regional scales, the starting phase of getting bio-energy 'off the ground' can be difficult. The supply and demand for biomass need to be matched over prolonged periods. Diversifying biomass supplies can be a key in creating a better biomass market. Flexible conversion capacity to deal with different biomass streams, as well as fossil fuels, is also important. And international trade in bio-energy can buffer supply fluctuations.

Production can also be started in niches. Major examples are the modernisation of power generation in the sugar, in paper and pulp, and in (organic) waste treatment. Regulations—such as acceptable payback tariffs for independent power producers—are essential. Niche markets can also be found for modern biofuels, such as high-value fuel additives, as mixes with gasoline, or for specific parts of a local transport fleet (such as buses). Successful biomass markets are working in Scandinavian countries and in Brazil (boxes 7.3 and 7.4).

Polygeneration of products and energy carriers. To compete with coal (chapter 8), biomass energy may have to follow a polygeneration strategy—coproducing electricity, fuels, fibres, and food from biomass. One example would be the generation of electricity by a BIG/CC plant as well as any fluid that can be produced from the syngas: methanol, dimethyl ether (DME), other

BOX 7.3. BRAZIL'S NATIONAL ALCOHOL PROGRAMME

PRO-ALCOOL in Brazil is the largest programme of commercial biomass utilisation in the world. Despite economic difficulties during some of its 25 years of operation, it presents several environmental benefits, reduces import expenditures, and creates jobs in rural areas.

Roughly 700,000 rural jobs in sugar-alcohol are distributed among 350 private industrial units and 50,000 private sugarcane growers. Moreover, the cost of creating a job in sugar-alcohol is much lower than in other industries. But mechanical harvesting could change this.

Despite a small reduction in harvested surface, Brazilian sugar-cane production has shown a continuous increase, reaching 313 million tonnes in the 1998/99 season. Alcohol consumption has been steady, even though almost no new hydrated ethanol powered automobiles are being produced. The decline in consumption from the partial age retirement of this fleet has been balanced by significant growth in the number of automobiles using a blend of 26 percent anhydrous ethanol in gasoline.

Subsidies were reduced in recent years in the southeast of Brazil, where 80 percent of the ethanol is produced, and then fully removed early in 1999. Some government actions—compulsory increases in the amount of ethanol blended in gasoline and special financial conditions for acquisition of new hydrated ethanol powered cars—have favoured producers. Very recently the alcohol price at the pump stations was reduced, triggering the interest of consumers and carmakers in hydrated ethanol cars. Other government policies may include tax reductions on new alcohol cars, 'green' fleets, and mixing alcohol-diesel for diesel motors.

Another promising option is the implementation of a large cogeneration programme for sugar and alcohol. Revenues from electricity sales could allow further reductions in the cost of alcohol production, although it is not yet enough to make it competitive with gasoline in a free market. Even so, production costs continue to come down from learning by doing.

The programme has positive environmental and economic impacts. In 1999 it resulted in an emission reduction of almost 13 mega-tonnes of carbon. And the hard currency saved by not importing oil totals $40 billion over the 25 years since alcohol's introduction.

BOX 7.4. BIOMASS USE IN SWEDEN

Sweden is probably the world leader in creating a working biomass market. Its use of biomass for energy purposes—domestic heating with advanced heating systems, district heating, and combined heat and power generation—has increased 4–5-fold in the past 10 years. And the average costs of biomass have come down considerably. Swedish forests have met this growing demand with ease.

The growing contribution of biomass has been combined with a big increase in the number of companies supplying wood and wood products and in the number of parties using biomass. As a result competition has led to lower prices, combined with innovation and more efficient biomass supply systems.

Some 14,000 hectares in short rotation willow plantations have been established. Sweden also imports some biomass, which make up only a small part of the total supply but keep prices low.

Sweden plans to increase the 20 percent share of biomass in the total primary energy supply to 40 percent in 2020, largely by extending and improving the use of residues from production forests and wood processing industries (NUTEK, 1996).

liquids using Fischer-Tropps synthesis (Larson and Jin, 1999a; Faaij and others, 1999). Another could combine biomass and fossil fuels to coproduce modern energy carriers (Oonk and others, 1997).

An accepted principle is that biomass production for energy should not conflict with food production.

Internalising external costs and benefits. Bio-energy can offer benefits over fossil fuels that do not show up in its cost—that is, it can offer externalities. Being carbon-neutral is one. Another is the very low sulphur content. A third is that biomass is available in most countries, while fossil fuels often need to be imported. The domestic production of bio-energy also brings macro-economic and employment benefits (Faaij, Meuleman, and others, 1998). It can offer large numbers of unskilled jobs (van den Broek and van Wijk, 1998). It has fewer external costs than (imported) coal and oil (Borjesson, 1999; Faaij, Meuleman, and others, 1998).

Policies. Carbon taxes, price supports, and long-running research and development (R&D) programmes are often central in gaining experience, building infrastructure developing technology, and fostering the national market. Scandinavia and Brazil—and to a somewhat less extent northwest Europe and the United States—show that modernisation is essential for realising the promise of biomass as an alternative energy source (Ravindranath and Hall, 1995). It may even help in phasing out agricultural subsidies.

Conclusion

- Biomass can make a large contribution to the future world's energy supply. Land for biomass production should not be a bottleneck, if the modernisation of conventional agricultural production continues. Recent evaluations indicate that if land surfaces of 400–700 million hectares were used for biomass energy production halfway into the 21st century, there could be no conflicts with other land-use functions and the preservation of nature.
- Bio-energy's current contribution of 45 ± 10 exajoules a year—of which probably 16 ± 6 exajoules a year is commercial—could increase to 100–300 exajoules a year in the 21st century.
- The primary use of biomass for modern production of energy carriers accounts for about 7 exajoules a year. Modern biomass energy production can play an important role in rural development.
- Although developing countries are the main consumers of biomass, the potential, production, and use of biomass in these countries are often poorly quantified and documented.
- Biomass can be used for energy production in many forms. The resource use, the technologies applied, and the set-up of systems will depend on local conditions, both physical and socioeconomic. Perennial crops offer cheap and productive biomass production, with low or even positive environmental impacts.
- Production costs of biomass can be $1.5–2 a gigajoule in many regions. Genetic improvement and optimised production systems—and multi-output production systems, cascading biomass, and multifunctional land use—could bring bio-mass close to the (expected) costs of coal.
- A key issue for bio-energy is modernising it to fit sustainable development. Conversion of biomass to modern energy carriers (electricity, fuels) gives biomass commercial value that can provide income and development for local (rural) economies.
- Modernised biomass use can be a full-scale player in the portfolio of energy options for the longer term. The production of electricity and fuels from lignocellulosic biomass are promising options. But they require the development of markets, infrastructure, key conversion technologies (BIG/CC), and advanced fuel production systems.
- Flexible energy systems combining biomass and fossil fuels are likely to become the backbone for low-risk, low-cost energy supply systems.

Wind Energy

Wind energy, in common with other renewable energy sources, is broadly available but diffuse. The global wind resource has been described in chapter 5. Wind energy was widely used as a source of power before the industrial revolution, but later displaced by fossil fuel use because of differences in costs and reliability. The oil crises of the 1970s, however, triggered renewed interest in wind energy technology for grid-connected electricity production, water pumping, and power supply in remote areas (WEC, 1994b).

In recent decades enormous progress has been made in the development of wind turbines for electricity production. Around 1980 the first modern grid-connected wind turbines were installed. In 1990 about 2,000 megawatts of grid-connected wind power was in operation world-wide—at the beginning of 2000, about 13,500 megawatts. In addition, more than 1 million water-pumping wind turbines (wind pumps), manufactured in many developing countries, supply water for livestock, mainly in remote areas. And tens of thousands of small battery-charging wind generators are operated in China, Mongolia, and Central Asia (chapter 10).

The potential of wind energy

The technical potential of onshore wind energy to fulfil energy needs is very large—20,000–50,000 terawatt-hours a year (chapter 5). The economic potential of wind energy depends on the economics of wind turbine systems and of alternative options. Apart from investment costs, the most important parameter determining the economics of a wind turbine system is annual energy output, in turn determined by such parameters as average wind speed, statistical wind speed distribution, turbulence intensities, and roughness of the surrounding terrain. The power in wind is proportional to the third power of the momentary wind speed.

Because of the sensitivity to wind speed, determining the potential of wind energy at a specific site is not straightforward. More accurate meteorological measurements and wind energy maps and handbooks are being produced and (mostly) published, enabling wind project developers to better assess the long-term economic performance of their projects.

In densely populated countries the best sites on land are occupied, and public resistance makes it difficult to realise new projects at acceptable cost. That is why Denmark and the Netherlands are developing offshore projects, despite less favourable economics. Sweden and the United Kingdom are developing offshore projects to preserve the landscape.

Resources offshore are much larger than those onshore, but to be interesting they have to be close to electric infrastructure. A comprehensive study by Germanische Lloyd and Garrad Hassan & Partners (Matthies and others, 1995) concluded that around 3,000 terawatt-hours a year of electricity could be generated in the coastal areas of the European Union (excluding Finland and Sweden). With electricity consumption in those 12 countries at about 2,000 terawatt-hours a year, offshore options should be included in assessments of the potential of wind electricity.

Development of installed wind power

In 1997 the installed wind power was about 7,400 megawatts, in 1998 close to 10,000 megawatts, and in 1999 another annual 3,600 megawatts was installed (BTM Consult, 1999 and 2000). Between 1994 and 1999 the annual growth of installed operating capacity varied between 27 and 33 percent. The electricity generated by wind turbines can be estimated at 18 terawatt-hours in 1998 and 24 terawatt-hours in 1999.

There are 29 countries that have active wind energy programmes. Most of the capacity added in 1998 (2,048 megawatts) was in four countries: for Germany 793 megawatts, for the United States 577 megawatts, for Spain 368 megawatts, and for Denmark 310 megawatts (table 7.6).

Based on an analysis of the national energy policies for the most relevant countries, BMT Consult expects the global installed power to grow to around 30,000 megawatts of electricity in 2004.

Several generic scenarios assess the growth of wind power in the coming decades. One of the most interesting—by BTM Consult for the FORUM for Energy & Development, presented at the COP-4 of the UN-FCCC in Buenos Aires in December 1998—addresses three questions. Can wind power contribute 10 percent of the world's electricity needs within three decades? How long will it take to achieve this? How will wind power be distributed over the world?

Two scenarios were developed. The *recent trends* scenario extrapolates current market development, while the *international agreements* scenario assumes that international agreements are realised. Both scenarios assumed that integrating up to 20 percent of wind power in the grid (in energy terms) would not be a problem with present grids, modern fossil fuel power plants, and modern wind turbines. Analysis of the world's exploitable wind resources, with growth of electricity demand as indicated in the *World Energy Outlook* (IEA, 1995 and 1996), led to the following conclusions:

- Under the recent trends scenario—starting with 20,000 megawatts by the end of 2002 and assuming a 15 percent cost reduction, and later 12 percent and 10 percent, for each doubling of the accumulated number of installations—10 percent penetration is

TABLE 7.6. INSTALLED WIND POWER, 1997 AND 1998

	Installed megawatts 1997	Cumulative megawatts 1997	Installed megawatts 1998	Cumulative megawatts 1998
Canada	4	26	57	83
Mexico	0	2	0	2
United States	29	1.611	577	2.141
Latin America	10	42	24	66
Total Americas	**43**	**1.681**	**658**	**2.292**
Denmark	285	1.116	310	1.420
Finland	5	12	6	18
France	8	13	8	21
Germany	533	2.081	793	2.874
Greece	0	29	26	55
Ireland	42	53	11	64
Italy	33	103	94	197
Netherlands	44	329	50	379
Portugal	20	39	13	51
Spain	262	512	368	880
Sweden	19	122	54	176
United Kingdom	55	328	10	338
Other Europe	13	57	23	80
Total Europe	**1.318**	**4.793**	**1.766**	**6.553**
China	67	146	54	200
India	65	940	52	992
Other Asia	9	22	11	33
Total Asia	**141**	**1.108**	**117**	**1.224**
Australia and New Zealand	2	8	26	34
Pacific Islands	0	3	0	3
North Africa (incl. Egypt)	0	9	0	9
Middle East	8	18	0	18
Former Soviet Union	1	19	11	19
Total other continents and areas	**11**	**57**	**37**	**83**
Annual installed capacity worldwide	**1.513**		**2.577**	
Cumulative capacity installed worldwide		**7.639**		**10.153**

Note: The cumulative installed capacity by the end of 1998 is not always equal to the 1997 data plus installed capacity during 1998, because of adjustments for decommissioned and dismantled capacity. *Source: BTM Consult, 1999.*

achieved around 2025, and saturation in 2030–35, at about 1.1 terawatt. In this scenario the cost of generating wind electricity would come down to $0.032 a kilowatt-hour (1998 level) on average, ± 15 percent (depending on wind speed, connection costs to the grid, and other considerations).

- Under the international agreements scenario—with the same starting conditions but a slightly different learning curve—growth is faster and 10 percent penetration is achieved around 2016, with saturation in 2030–35 at about 1.9 terawatts. In this scenario the cost would come down to $0.027 a kilowatt-hour on average, again ± 15 percent.

In this second scenario, the regional distribution of wind power is North America 23 percent, Latin America 6 percent, Europe (Eastern and Western) 14 percent, Asia 23 percent, Pacific OECD 8 percent, North Africa 5 percent, former Soviet Union 16 percent, and rest of the world 5 percent.

Technology developments

Wind turbines become larger. From the beginning of the modern wind energy technology era in the mid-1970s, there has been gradual growth in the unit size of commercial machines. In the mid-1970s the typical size of a wind turbine was 30 kilowatts of generating capacity, with a rotor diameter of 10 metres. The largest units installed in 1998 had capacities of 1,650 kilowatts with rotor diameters of 66 metres. By 1999, 460 units with a generating capacity of 1 megawatt or more were installed world-wide. Turbines with an installed power of 2 megawatts (70 metres diameter) are being introduced in the market, and 3–5 megawatt machines are on the drawing board (table 7.7).

Market demands drive the trend towards larger machines: economies of scale, less visual impacts on the landscape per unit of installed power, and expectations that offshore potential will soon be developed. The average size of wind turbines installed is expected to be 1,200 kilowatts before 2005 and 1,500 kilowatts thereafter. Note, however, that the optimum size of a turbine—in cost, impact, and public acceptance—differs for onshore (nearby as well as remote) and offshore applications.

Wind turbines become more controllable and grid-compatible. The output of stall regulated wind turbines is hardly controllable, apart from switching the machine on and off. Output varies with the wind speed until reaching the rated wind speed value. As the application of the aerodynamic stall phenomena to structural compliant machines gets more difficult with bigger turbines, blade pitch control systems are being applied to them. For structural dynamics and reliability, a blade-pitch system should be combined with a variable speed electric conversion system. Such systems typically incorporate synchronous generators combined with electronic AC-DC-AC converters.

TABLE 7.7. AVERAGE SIZE OF INSTALLED WIND TURBINES, 1992–99

Year	Size (kilowatts)
1992	200
1994	300
1996	500
1998	600
1999	700

Modern electronic components have enabled designers to control output—within the operational envelope of the wind speed—and produce excellent power quality. These developments make wind turbines more suitable for integration with the electricity infrastructure and ultimately for higher penetration. These advantages are of particular interest for weak grids, often in rural and remote areas that have a lot of wind.

Wind turbines will have fewer components. For lower costs and greater reliability and maintainability, designers now seek technology with fewer components—such as directly driven, slow-running generators, with passive yaw and passive blade pitch control. In Germany 34 percent of the installed power in 1998 (770 megawatts) was realised with this type of technology.

Special offshore designs are on the drawing board. With the first offshore wind farms in Europe, industrial designers are developing dedicated turbine technologies for large wind farms in the open sea (Beurskens, 2000). Outages onshore can often be corrected quickly so that only a small amount of energy is lost. But offshore the window for carrying out repairs or replacing components is often limited. The high cost of complete installations implies the use of large wind turbines, which will probably have installed powers of 3–6 megawatts. Offshore design features will include novel installation concepts, electricity conversion and transport systems, corrosion protection, and integration with external conditions (both wind and wave loading).

Time to market is becoming shorter than project preparation time. Although there is a temporary shortage of supply of wind turbines in some countries, competition among manufacturers is fierce. One way to become more competitive is to keep implementing innovations and component improvements to reduce cost. Times to market new products are also becoming short (two to three years). As a result, just as the construction of a wind farm commences, the technology is already outdated.

System aspects

Wind turbines deliver energy, but little capacity. Because wind energy is intermittent, wind turbines mainly deliver energy, but little capacity value often 20 percent or less of the installed wind power. And this percentage falls when the penetration of wind turbines increases, requiring even more back-up power for a reliable energy supply. But wind-generated electricity can be transformed from intermittent to baseload power if it is combined with, say, compressed air energy storage. In this way a high capacity factor can be achieved with a small economic penalty, potentially about $0.01 a kilowatt-hour (Cavallo, 1995). This option becomes attractive when wind electricity generation costs fall below $0.03 a kilowatt-hour. It also opens the possibility of exploiting wind resources remote from markets, as in the Great Plains of the United States (Cavallo, 1995) and in inner Mongolia and northwest China (Lew and others, 1998).

> Industrial designers are developing dedicated turbine technologies for large wind farms in the open sea.

Wind power becomes more predictable. Meteorological research on predicting the output of wind farms a few hours in advance has produced computer programs that optimise the operational and fuel costs of regional electricity production parks (Denmark, Germany). This will increase the capacity value of wind power and the value of the electricity produced.

Capacity factors are somewhat adjustable. Some general misconceptions sometimes lead to the wrong decisions or conclusions. The capacity factor (annual energy output/output based on full-time operation at rated power) depends on local winds and wind turbines. By optimising the turbine characteristics to the local wind regime, the capacity factor—now often 20–25 percent—can be optimised without losing too much energy output. But extreme capacity factors—say, 40 percent—automatically means a large loss of potential energy output.

Renewed interest in autonomous systems. In the mid-1980s interest grew in the application of wind turbines in isolated areas without an energy infrastructure. Two systems can be distinguished:

- Hybrid systems, in which a wind turbine operates in parallel with, for example, a diesel set (to save fuel consumption and to decrease maintenance and repairs) or a diesel generator combined with a battery storage unit.
- Standalone units, for charging batteries, pumping water for irrigation, domestic use, watering cattle, or desalination and cooling.

More than 30 experimental hybrid systems have been developed and tested, almost all stopped without a commercial follow up, because of unreliable and expensive components. The interest in hybrid and standalone systems is being revived—initiated by the search for new markets for renewable energy systems and influenced by spectacular improvements in performance and cost for wind turbines and power electronics (box 7.5 and chapter 10). For successful market entry, systems have to be modular, and standards for components and subsystems introduced.

Small battery-charging wind generators are manufactured by the thousand in China, Mongolia, and elsewhere, making them more numerous than larger diameter wind generators. Although their contribution to world energy supply is negligible, their potential impact on the energy needs of rural and nomadic families is significant (as with photovoltaic home systems).

Environmental aspects

Environmental aspects come into play in the three phases of a wind turbine project: building and manufacturing, normal operation during the turbine's lifetime, decommissioning.

Building and manufacturing. No exotic materials or manufacturing processes are required in producing a wind turbine or building the civil works. The energy payback time of a large wind turbine, under typical Danish conditions, is 3 to 4 months (Dannemand Andersen, 1998).

Normal operation. Negative environmental aspects connected to the use of wind turbines are: acoustic noise emission, visual impact on the landscape, impact on bird life, moving shadows caused by the rotor, and electromagnetic interference with radio, television, and radar signals. In practice the noise and visual impact cause the most problems. Acoustic noise emission prevents designers from increasing the tip speed of rotor blades, which would increase the rotational speed of the drive train shaft and thus reduce the cost of gearboxes or generators. Aero-acoustic research has provided design tools and blade configurations to make blades considerably more silent, reducing the distance needed between wind turbines and houses.

The impact on bird life appears to be minor if the turbines are properly located. A research project in the Netherlands showed that the bird casualties from collisions with rotating rotor blades on a wind farm of 1,000 megawatts is a very small fraction of those from hunting, high voltage lines, and vehicle traffic (Winkelman, 1992). In addition, acoustic devices might help prevent birds from flying into rotor blades (Davis, 1995).

During normal operation a wind turbine causes no emissions, so the potential to reduce carbon dioxide emissions depends on the fuel mix of the fossil-fuelled plants the wind turbine is working with. A study by BTM Consult (1999) indicates that in 2025 wind energy could prevent the emission of 1.4–2.5 gigatonnes of carbon dioxide a year.

Decommissioning. Because all components are conventional, the recycling methods for decommissioning the wind turbine are also conventional. Most blades are made from glass or carbon fibre

BOX 7.5. HYBRID WIND, BATTERY, AND DIESEL SYSTEMS IN CHINA

Since 1994 the 360 inhabitants of the village of Bayinaobao in Inner Mongolia have been provided with electricity from a hybrid electricity system that employs two 5-kilowatt wind turbines, a battery storage unit, and a diesel generator. In this system the wind turbines provide about 80 percent of the electricity generated. The technology is being developed under a German-Chinese industrial joint venture aimed at transferring the German-developed wind turbine and ancillary technologies. By the time 140 systems have been built, local content should account for about 70 percent of the wind turbine technology, reducing the cost of an imported system by half. Based on the performance of the first unit and the costs projected for components, the electricity from the hybrid system will cost less (up to 22 percent less, at a diesel fuel price of $0.38 a litre) than from the conventional diesel system (Weise and others, 1995).

reinforced plastics, processed by incineration. To replace glass and carbon and close the cycle of material use, wood composites are being applied and biofibres developed.

Economic aspects

The energy generation costs of wind turbines are basically determined by five parameters:

- *Turnkey project cost.* Initial investment costs (expressed in U.S. dollars a square metre of swept rotor area), project preparation, and infrastructure make up the turnkey project costs. The costs of European wind turbines are typically $410 a square metre (machine cost, excluding foundation). Project preparation and infrastructure costs depend heavily on local circumstances, such as soil conditions, road conditions, and the availability of electrical substations. Turnkey costs vary from $460 a square metre to $660 a square metre (with 1 ECU = 1.1 U.S. dollar).
- *Energy output of the system.* The energy output of a wind turbine can be estimated by $E = b.\ V^3$ kilowatt-hours a square metre, where E is the annual energy output, *b* is the performance factor, and V is the average wind speed at hub height. The factor *b* depends on the system efficiency of the wind turbine and the statistical distribution of wind speeds. In coastal climates in Europe a value of 3.15 for *b* is representative for modern wind turbines and not too far away from the theoretical maximum. On good locations in Denmark, northern Germany, and the Netherlands annual outputs of more than 1,000 kilowatt-hours a square metre are often achieved.
- *Local average wind speed.* In general, local average wind speed should exceed five metres a second at a height of 10 metres to allow economic exploitation of grid-connected wind turbines.
- *Availability of the system.* The technical availability of modern wind farms exceeds 96 percent.
- *Lifetime of the system.* Design tools have improved so much that designing on the basis of fatigue lifetime has become possible. As a result one can confidently use lifetimes of 15–20 years for economic calculations.

For Europe a state-of-the-art reference calculation uses the following values:

Turnkey cost	$600 a square metre
Interest	5 percent
Economic lifetime	15 years
Technical availability	95 percent
Annual energy output	$3.15\ V^3$ kilowatt-hours a square metre
O & M costs	$0.005 a kilowatt-hour

If average wind speeds at the hub height range from 5.6–7.5 metres a second, the corresponding electricity production cost is $0.12–0.05 a kilowatt-hour. Because the energy of the wind is proportional to the third power of the wind speed, the economic calculations are very sensitive to the local average annual wind speed.

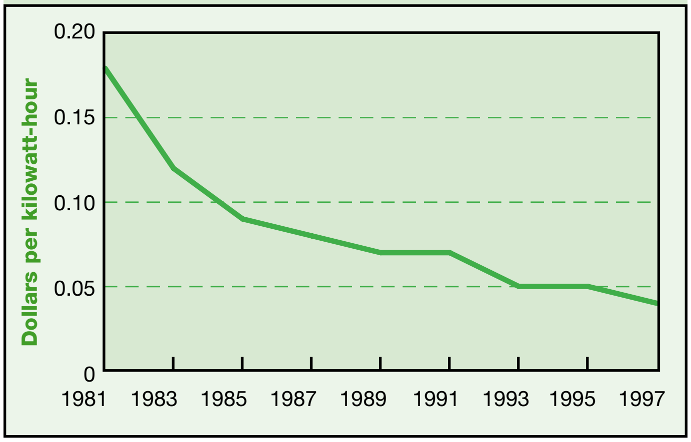
Figure 7.2 illustrates the cost reductions for electricity generation from wind turbines in Denmark since 1981. But take care in translating these figures to other regions, for the cost of project preparation, infrastructure, and civil works in Denmark is low relative to many other regions. BTM Consult (1999) expects a 35–45 percent reduction in generation costs in the next 15–20 years (figure 7.3).

Implementation issues

Manufacturers and project developers usually identify the following items as serious barriers for efficient implementation of wind turbine projects:

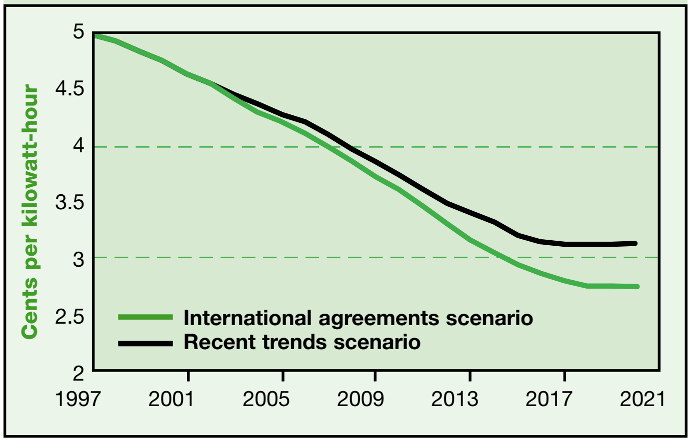
- Fluctuating demand for wind turbines as a result of changing national policies and support schemes.
- Uncertainties leading to financing costs as a result of changing governmental policies.

FIGURE 7.2. DEVELOPMENT OF WIND ELECTRICITY GENERATION COSTS IN DENMARK, 1981–1997



Source: BTM Consult, 1999.

FIGURE 7.3. POTENTIAL COST REDUCTIONS FOR WIND POWER, 1997–2020



Source: BTM Consult, 1999.

- Complicated, time-consuming, and expensive institutional procedures, resulting from a lack of public acceptance, which varies considerably from country to country.
- Project preparation time often longer than the 'time to market' of new wind turbine types.
- Lack of sufficient international acceptance of certification procedures and standards.

Denmark and the United States were the first to introduce an integrated approach to wind energy, encompassing both technical development and the introduction of market incentives. Now more than 25 countries use a great variety of incentives, some very successful and some complete failures. The applied incentive schemes can be grouped in three categories, or in combinations of these categories:

- Fixed tariff systems, such as those of Denmark, Germany, and Spain (favourable payback tariffs are fixed for a period of, say, 10 years).
- Quota or concession systems, such as the Non Fossil Fuel Obligation of England and the systems of France, Ireland, and Scotland (competitive bidding for projects until a set amount of electricity production is realised).
- Other systems to stimulate the application of wind energy, such as tax breaks, carbon taxes, green electricity, and tradable green labels.

With the first schemes, Denmark, Germany, and Spain installed many more wind turbines than countries using other schemes. Elsewhere in Europe, the second system has demonstrated success also (table 7.8). But none of the schemes can be easily translated from one country to another. Legal circumstances and public acceptance may differ completely. Moreover, several incentives have been introduced only recently, and their effectiveness is not yet known.

Under favourable legislation and general acceptance by the public, a fixed tariff system may be quite successful, because it provides financial security to project developers, owners, and financiers. In the long term, however, fixed tariffs will become too expensive to subsidise if they are not modified. As a result the industry might collapse unless the incentive program brings the cost of the technology down. Quota systems based on calls for tenders only once in two or three years may lead to extreme fluctuations in the market growth. Concessions appear interesting for harnessing large, high-quality wind resources in regions remote from major electricity markets (PCAST, 1999). However, very large wind projects for remote wind resources require a different industry structure from today's. Needed are large project developers with deep financial pockets—not wind turbine suppliers. The installation of wind turbines can also increase if individuals, groups of individuals, or cooperatives are allowed to own one or more wind turbines as small independent power producers (IPPs) and to sell electricity to the grid.

It is too early to judge whether tradable green certificates, connected to a quota system, are viable. Marketing green electricity seems to develop successfully only when the public recognises green electricity as a product different from regular electricity, worth the additional costs.

TABLE 7.8. TYPE OF INCENTIVE AND WIND POWER ADDED IN 1998

Type of incentive	Country	Megawatts added	Percentage increase
Fixed tariffs	Denmark	310	28
	Germany	793	38
	Spain	368	72
	Total	**1,471**	**40**
Quota or concession systems	France	8	62
	Ireland	11	21
	United Kingdom	10	3
	Total	**29**	**7**

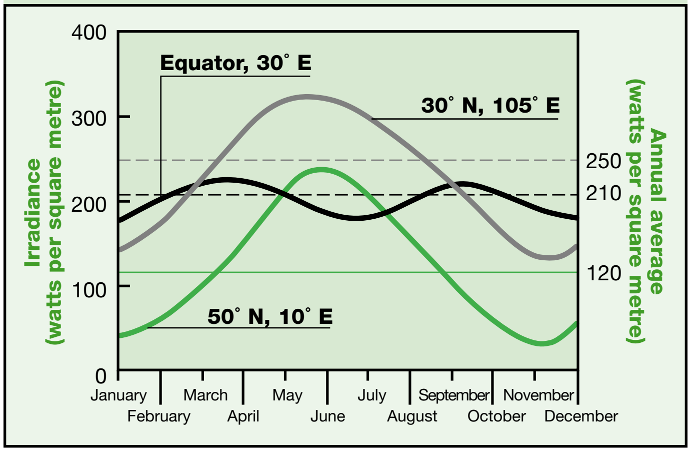
Conclusion

- The potential of wind energy is large, with the technical potential of generating electricity onshore estimated at 20,000–50,000 terawatt-hours a year.
- When investigating the potential, special attention should go to possibilities offshore. Studies for Europe indicate that the offshore wind resources that can be tapped are bigger than the total electricity demand in Europe.
- The average growth rate of the cumulative capacity over the last six years has been about 30 percent a year, bringing the cumulative installed wind turbine capacity to about 10,000 megawatts at the end of 1998 and about 13,500 megawatts at the end of 1999—and wind energy production to 18 terawatt-hours in 1998 and 24 terawatt-hours in 1999.
- Wind turbines are becoming larger, with the average size installed in 1998 at 600 kilowatts, up from about 30 kilowatts in the mid-1970s. Turbines of megawatt size are being developed and should soon be commercially available.
- Costs have to come down further, requiring development of advanced flexible concepts and dedicated offshore wind energy systems. Cost reductions up to 45 percent are feasible within 15 years. Ultimately wind electricity costs might come down to about $0.03 a kilowatt-hour.
- Although wind-generated electricity is an intermittent resource, it can be transformed to baseload power supply if combined with energy storage. For compressed air energy storage the additional costs may be limited to about $0.01 a kilowatt-hour, opening the possibility of exploiting good wind resources remote from markets.
- The environmental impacts of wind turbines are limited, with noise and visibility causing the most problems, increasing public resistance against the installation of new turbines in densely populated countries.
- Interest in small turbines is being revived for standalone and autonomous systems in rural areas.

Photovoltaic solar energy

Photovoltaic solar energy conversion is the direct conversion of sunlight into electricity. This can be done by flat plate and concentrator systems.

FIGURE 7.4. VARIATIONS IN AVERAGE MONTHLY INSOLATION OVER THE YEAR IN THREE LOCATIONS



Source: Eliasson, 1998.

TABLE 7.9. POTENTIAL CONTRIBUTION OF SOLAR ENERGY TECHNOLOGIES TO WORLD ENERGY CONSUMPTION ACCORDING TO DIFFERENT STUDIES (EXAJOULES OF ELECTRICITY)

Study	2020–2025	2050	2100
WEC, 1994 a,b	16		
IIASA and WEC, 1998	2–4	7–14	
RIGES, 1993 (solar and wind)	17	35	
Shell, 1996	<10	200	
Greenpeace and SEI, 1993 (solar and wind)	90	270	830
Reference: total world energy consumption	400–600	400–1,200	

An essential component of these systems is the solar cell, in which the photovoltaic effect—the generation of free electrons using the energy of light particles—takes place. These electrons are used to generate electricity.

Characteristics of the source

Solar radiation is available at any location on the surface of the Earth. The maximum irradiance (power density) of sunlight on Earth is about 1,000 watts a square metre, irrespective of location. It is common to describe the solar source in terms of insolation—the energy available per unit of area and per unit of time (such as kilowatt-hours per square metre a year). Measured in a horizontal plane, annual insolation varies over the Earth's surface by a factor of 3—from roughly 800 kilowatt-hours per square metre a year in northern Scandinavia and Canada to a maximum of 2,500 kilowatt-hours per square metre a year in some dry desert areas.

The differences in average monthly insolation (June to December) can vary from 25 percent close to the equator to a factor of 10 in very northern and southern areas (figure 7.4), determining the annual production pattern of solar energy systems. The ratio of diffuse to total annual insolation can range from 10 percent for bright sunny areas to 60 percent or more for areas with a moderate climate, such as Western Europe. The actual ratio largely determines the type of solar energy technology that can be used (non-concentrating or concentrating).

The potential of photovoltaic solar energy

The average power density of solar radiation is 100–300 watts a square metre. The net conversion efficiency of solar electric power systems (sunlight to electricity) is typically 10–15 percent. So substantial areas are required to capture and convert significant amounts of solar energy to fulfil energy needs (especially in industrialised countries, relative to today's energy consumption). For instance, at a plant efficiency of 10 percent, an area of 3–10 square kilometres is required to generate an average of 100 megawatts of electricity—0.9 terawatt-hours of electricity or 3.2 petajoules of electricity a year—using a photovoltaic (or solar thermal electricity) system.

The total average power available at the Earth's surface in the form of solar radiation exceeds the total human power consumption by roughly a factor of 1,500. Calculated per person, the average solar power available is 3 megawatts, while the consumption varies from 100 watts (least industrialised countries) to 10 kilowatts (United States), with an average of 2 kilowatts. Although these numbers provide a useful rough picture of the absolute boundaries of the possibilities of solar energy, they have little significance for the technical and economic potential. Because of differences in the solar energy supply pattern, energy infrastructure, population density, geographic conditions, and the like, a detailed analysis of the technical and economic potential of solar energy is best made regionally or nationally. The global potential is then the sum of these national or regional potentials.

The *economic* potential of solar energy, a matter of debate, depends on the perspectives for cost reduction. In the recent past several scenario studies have assessed the potential application of solar energy technologies (IIASA and WEC, 1998; WEC, 1994a,b; Johansson and others, 1993a; Shell, 1996; Greenpeace and SEI, 1993). They provide a picture of different views on the potential penetration of solar energy in the 21st century (table 7.9).

The *technical* potential of photovoltaics has been studied in some detail in several countries. In densely populated countries with a well-developed infrastructure, there is an emphasis on applications of grid-connected photovoltaic systems in the built environment (including infrastructural objects like railways and roads). These systems are necessarily small- or medium-sized, typically 1 kilowatt to 1 megawatt.[1] The electricity is generated physically close to the place where electricity is also consumed. In less densely populated countries there is also considerable interest in ‘ground-based’ systems, generally larger than 1 megawatt. The area that would be required to generate an average electrical power equal to the total present human power consumption—assuming 10 percent plant efficiency and an insolation of 2,000 kilowatt-hours per square metre a year—is roughly 750 x 750 square kilometres. In countries or rural regions with a weak or incomplete grid infrastructure, small standalone systems and modular electric systems may be used for electrification of houses or village communities.

Photovoltaic market developments

Between 1983 and 1999 photovoltaic shipments grew by just over 15 percent a year (figure 7.5). In 1998 around 150 megawatts of solar cell modules were produced, in 1999 nearly 200 megawatts. In 1998 cumulative production was around 800 megawatts. Probably about 500 megawatts, perhaps 600 megawatts, of this production was in operation in 1998, generating about 0.5 terawatt-hours a year. In 1993–98 operating capacity increased by roughly 30 percent a year.

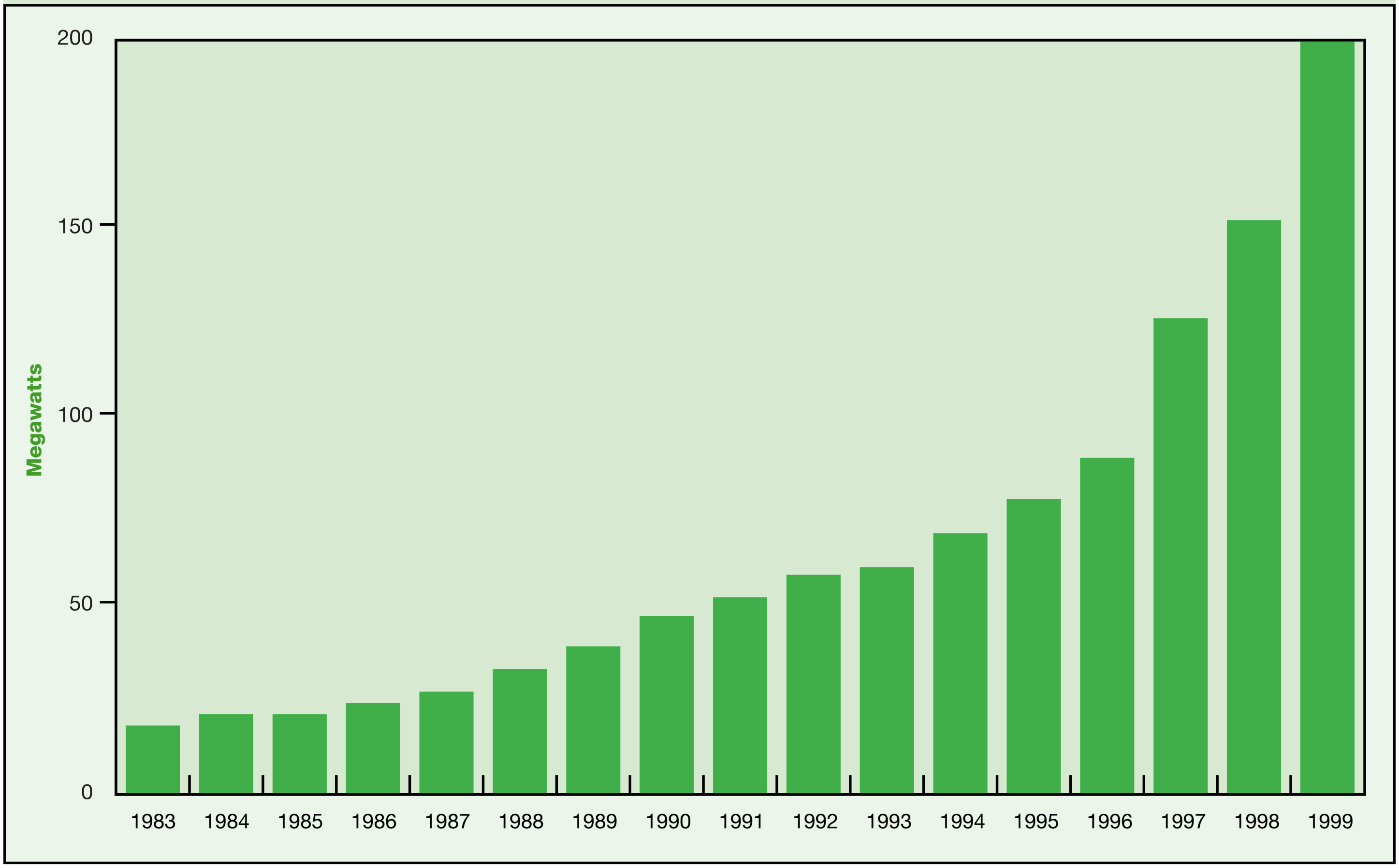
In 1990–94 the market share of solar home systems and village power systems was 20 percent (based on power volume). Grid-connected systems accounted for 11 percent, with the rest for water pumping, communication, leisure, consumer products, and the like (EPIA and Altener, 1996). In 1995–98 the relative importance of grid-connected systems increased to 23 percent (Maycock, 1998).

Current status and future development of photovoltaic solar cells and modules

The major component of photovoltaic solar energy systems is the solar module, normally a number of solar cells connected in series. The efficiency of an ideal photovoltaic cell is about 30 percent at most (for a single cell under natural sunlight). Higher efficiencies can be achieved by stacking cells with different optical properties in a tandem device, by using concentrator cells, or by combining these two. The efficiency of practical solar cells is determined by several loss mechanisms. An overview of efficiencies achieved through 1999 for different cells and modules is given in table 7.10.

Solar cells and their corresponding modules can be divided into two main categories: wafer-type and thin-film. Wafer-type cells are made from silicon wafers cut from a rod or ingot, or from silicon

FIGURE 7.5. PHOTOVOLTAIC SHIPMENTS, 1983–1999



Source: Based on a Maycock, 1998; PVIR, 1999.

TABLE 7.10. IMPORTANT PHOTOVOLTAIC SOLAR CELL AND MODULE TECHNOLOGIES

Technology	Symbol	Characteristic	Record efficiency laboratory cells (percent)	Typical efficiency commercial flat-plate modules (percent)
Single crystal silicon	sc-Si	Wafer-type	24	13–15
Multi-crystalline silicon	mc-Si	Wafer-type	19	12–14
Crystalline silicon films on ceramics	f-Si	Wafer type	17	(8–11)
Crystalline silicon films on glass		Thin film	9	
Amorphous silicon (including silicon-germanium tandems)	a-Si	Thin film	13	6– 9
Copper-indium/gallium-diselenide	CIGS	Thin film	18	(8–11)
Cadmium telluride	CdTe	Thin film	16	(7–10)
Organic cells (including dye-sensitised titanium dioxide cells)		Thin film	11	
High-efficiency tandem cells	III-V	Wafer-type and thin film	30	
High-efficiency concentrator cells	III-V	Wafer-type and thin-film	33 (tandem) 28 (single)	

Note: Numbers in parentheses are results from pilot production or first commercial production.

Source: Green and others, 1999.

ribbons. Thin-film cells are deposited directly onto a substrate (glass, stainless steel, plastic). For flat-plate applications, the individual cells are connected in series to form a module. Solar cells for concentrator systems are mounted in a one-dimensional or two-dimensional optical concentrator.

For the technologies in table 7.10, sc-Si, mc-Si, and a-Si are fully commercial, with the first two taking 85 percent of the 1998 commercial market, and the third 13 percent. (PVIR, 1999). CIGS and CdTe are emerging commercial technologies, whereas f-Si and one form of crystalline silicon films on glass appear to be in a pilot production phase. Organic cells are still in a laboratory stage, though dye-sensitised titanium dioxide cells are considered for near-term indoor applications. High-efficiency cells are used in concentrator systems.

It is still too early to identify winners or losers among the photovoltaic technologies under development or in production. There is reasonable consensus that thin-film technologies generally offer the best long-term perspective for very low production cost. But crystalline silicon wafer technology also still has a huge potential for cost reduction through economies of scale and technological improvements. This perspective recently triggered major investments in new production capacity. So it is not yet clear when thin films will become dominant in the photovoltaics market.

The conversion efficiency of commercial modules should increase steadily over the next decades (irrespective of the technology). For the medium term (2010) the efficiency is likely to be about 12–20 percent (Maycock, 1998), and for the longer term (beyond 2020) possibly 30 percent or even somewhat more (EUREC Agency, 1996). Note, however, that this is based on an evaluation of what is physically possible, not on what could be done technologically at low cost. Moreover, it is not expected that these high efficiencies can be obtained by simple extrapolation of today's commercial technologies. It is not very likely that modules with the lowest manufacturing cost per watt have the highest efficiency.

System aspects

Photovoltaic system components. To make use of the electricity from photovoltaic cells and modules, one has to build a complete system, also comprising electronic parts, support structures, and sometimes electricity storage. It is customary to use the term balance-of-system (BOS) for the sum of system components and installation excluding modules.

Type and size of photovoltaic systems. Photovoltaics can be used in a wide variety of applications, from consumer products and small standalone units for rural use (such as solar home systems and solar lanterns) to grid-connected rooftop systems and large power stations. Typical system size varies from 50 watts to 1 kilowatt for standalone systems with battery storage, from 500 watts to 5 kilowatts for rooftop grid-connected systems, and from 10 kilowatts to many megawatts for grid-connected ground-based systems and larger building-integrated systems. Of these market segments, rural electrification for sustainable development and building-integrated systems (as forerunners of large-scale implementation) are expected to grow rapidly because of concentrated marketing efforts and financial incentives.

Need for storage. Because photovoltaic modules offer an intermittent source of energy, most standalone systems are equipped with battery storage (usually a lead-acid battery) to provide energy during the night or during days with insufficient sunshine. In some cases batteries store energy during longer periods. When using grid-connected photovoltaic systems, the grid serves as 'virtual storage': electricity fed into the grid by photovoltaics effectively reduces the use of fuel by power plants fired by coal, oil, or gas.

> The total average power available at the Earth's surface in the form of solar radiation exceeds the total human power consumption by roughly a factor of 1,500.

Performance ratio of photovoltaic systems. It is of great practical importance to be able to predict the actual energy that a photovoltaic system of a certain size feeds into the grid. But that requires reliable information on the insolation in the plane of the system, on the system power under standard test conditions, and on the system losses. For simplicity, all system losses in grid-connected photovoltaic systems are taken together in the performance ratio, which is the ratio of the time-averaged system efficiency to the module efficiency under standard conditions. For grid-connected photovoltaic systems the state-of-the-art performance ratio, now typically 0.75–0.85, could increase to 0.9 in the longer term. For state-of-the-art standalone systems the typical performance ratio is 0.6.

Environmental aspects

Environmental life-cycle analysis. Solar technologies do not cause emissions during operation, but they do cause emissions during manufacturing and possibly on decommissioning (unless produced entirely by 'solar breeders'). With the industry growing, there is now considerable interest in environmental aspects of solar technologies. Environmental life-cycle analyses of photovoltaic systems and components (Alsema and Nieuwlaar, 1998) are already leading to the development of different materials and processes in the manufacturing of photovoltaic modules (see Tsuo and others, 1998). An example is developing water-based pastes instead of pastes based on organic solvents for screen printing. In addition, several recycling processes have been developed for off-spec or rejected modules.

Energy payback time. One of the most controversial issues for photovoltaics is whether the amount of energy required to manufacture a complete system is smaller or larger than the energy produced over its lifetime. Early photovoltaic systems were net consumers of energy rather than producers. In other words, the energy payback time of these systems was longer than their lifetime. This situation has changed and modern grid-connected rooftop photovoltaic systems now have payback times much shorter than their (expected) technical lifetime of roughly 30 years (Alsema, Frankl, and Kato, 1998) (table 7.11).

For grid-connected ground-based systems the energy payback time of the balance of system is longer than for rooftop systems, because of materials used in foundation and support. The energy payback time, now three to nine years, will decrease to one to two years.

For standalone photovoltaic systems with battery storage (such as solar home systems) the situation is less favourable than for grid-connected systems, because of the long energy payback time associated with the (lead-acid) battery. At an insolation of 2,000 kilowatt-hours per square metre a year, the energy payback time of modern solar home systems is now seven to 10 years (Alsema and Nieuwlaar, 1998). This number may come down to roughly six years, of which five are due to the battery. Since the technical lifetime of a battery in a photovoltaic system is usually five years or less, the direct effectiveness of (present generation) solar home systems for the reduction of greenhouse gas emissions is a matter of debate.

Carbon dioxide mitigation potential. The carbon dioxide mitigation potential of photovoltaics can be roughly inferred from the data on energy payback time, assuming that emissions of greenhouse gases (SF_6 and CF_4) related to photovoltaic cell and module production are effectively minimised. As an example, a photovoltaic system with an energy payback time of two years at 1,500 kilowatt-hours per square metre a year and a technical lifetime of 30 years (ratio 1:15) will produce 15 kilowatt-hours of electricity without emissions for each kilowatt-hour of electricity 'invested' in manufacturing. Specific carbon dioxide emissions are therefore fifteen times lower than those of the relevant fuel mix—the mix used in supplying the total photovoltaics industry chain with energy.

Materials availability. The crystalline silicon photovoltaics industry has so far used off-grade material from the semiconductor industry as its feedstock. Very fast growth of the crystalline silicon photovoltaics industry would require dedicated production of 'solar grade' silicon (Bruton and others, 1997). Although several processes for solar grade silicon have been developed to a laboratory scale, none has been taken into commercial production. It is expected, however, that new feedstock can be made available in time if necessary. The availability of some of the elements in thin-film photovoltaic modules (like indium and tellurium) is a subject of concern. There apparently are no short-term supply limitations, but the match between demand from the photovoltaics industry and world market supply may become an issue at very large (multiple gigawatts a year) production levels (Johansson and others, 1993b). CdTe and CIGS may therefore be valuable bridging technologies (Andersson, 1998).

TABLE 7.11. ESTIMATED ENERGY PAYBACK TIME OF GRID-CONNECTED ROOFTOP PHOTOVOLTAIC SYSTEMS (YEARS)

	State of the art	Near to medium term (<10 years)	Long term
Modules			
Crystalline silicon	3–8	1.5–2.5	<1.5
Thin film	2–3	0.5–1.5	<0.5
Balance of system	<1	0.5	<0.5
Total system			
Crystalline silicon	4–9	2–3	<2
Thin film	3–4	1–2	<1

Note: Based on an insolation of 1,500 kilowatt-hours per square metre a year.

Source: Alsema, Frankl and Kato, 1998.

> It is still too early to identify winners or losers among the photovoltaic technologies under development or in production.

Health. Of special concern is the acceptance of cadmium-containing photovoltaic modules. The cadmium content of CdTe (and CIGS) modules appears to be well within limits for safe use (Alsema and Nieuwlaar, 1998). And production processes can fulfil all applicable requirements. But political and public acceptance is not automatic. Therefore, there are efforts to eliminate cadmium from CIGS modules even at the cost of a reduced efficiency. Also a closed cycle for reclaiming and recycling of disposed CdTe modules has been developed (Bohland and others, 1998).

Economic aspects

Photovoltaic system cost. The turnkey cost of a photovoltaic system is determined by the module cost and by the balance-of-system (BOS) costs, which contains the cost of all other system components, electrical installation costs, and costs associated with building integration, site preparation, erection of support structures, and so on. The turnkey price is generally 20–40 percent higher than the *cost.*

In 1998 photovoltaic module prices were $3–6 a watt, depending on supplier, type, and size of order (Maycock, 1998; IEA PVPS, 1998). The prices of complete photovoltaic systems vary widely with system type and size, and from country to country (Thomas and others, 1999; IEA PVPS, 1998). But $5–10 a watt for grid-connected systems and $8–40 a watt for standalone systems are considered representative today.

The future cost and price reduction of photovoltaic modules and systems can be evaluated in two ways. The first is by detailed analysis of manufacturing costs for a specific technology as function of technology improvements and innovations—and of production volumes. The second is by general analysis of photovoltaic markets and industries, using a learning curve approach. (Note that the second approach deals with prices rather than costs.)

- *Approach 1.* For crystalline silicon technologies, the manufacturing cost of solar cell modules can be reduced from the present $3–4 a watt down to $1.5–2 a watt in the short term and to around $1 a watt in the longer term. For thin films (a-Si, CdTe, and CIGS), the module costs are expected to fall to $1–1.5 a watt in the short term, $0.5–1 a watt in the longer term (Carlson and Wagner, 1993; Bruton and others, 1997; Little and Nowlan, 1997; Maycock, 1998). EUREC Agency (1996, p.84) even mentions module costs as low as $0.30 a watt. The corresponding prices are again 20–40 percent higher.

  The balance-of-system costs for rooftop and ground-based grid-connected systems are now typically $2–6 a watt. Improvements and economies of scale in power electronics, integration in the building process, and standardisation will enable reductions to $1–2 a watt in the short term, $0.5 a watt in the longer term. The turnkey system cost is therefore expected to decrease to $2–4 a watt in the short to medium term and to $1.0–1.5 a watt in the longer term. Ultimately (after 2015) system costs around or even below $1 a watt are foreseen (Johansson and others, 1993b; WEC, 1994b; Böer, 1998), resulting in prices of roughly $1 a watt (table 7.12). For such extremely low prices it is necessary to use very cheap modules with high efficiencies (15–30 percent), to reduce area-related balance of system costs.

TABLE 7.12. POSSIBLE COSTS OF GRID-CONNECTED PHOTOVOLTAIC SYSTEMS, BASED ON DIFFERENT EVALUATIONS OF PHOTOVOLTAIC PRODUCTION TECHNOLOGIES (APPROACH 1) (1998 DOLLARS PER WATT)

Element	1998	Short term (to 2005)	Medium term (2005–15)	Long term (after 2015)
Modules	3–4	1–2	0.5–1.0	≤ 0.5
Balance of system	2–6	1–2	0.5–1.0	≤ 0.5
Turnkey systems	5–10	2–4	1–2	≤ 1.0

Note: Prices are 20–40 percent higher than costs.

- *Approach 2.* An evaluation of the development of photovoltaic (mostly module) costs and prices using a learning curve can be found in IIASA and WEC (1998), Maycock (1998), ECN (1999b), and elsewhere. For 1975–97 the learning rate has been roughly 20 percent: prices have been reduced by 20 percent for each doubling of the cumulative sales. When the technology and market mature, as for gas turbines, the learning rate may fall to 10 percent (IIASA and WEC, 1998). It is not clear, however, whether this will apply to photovoltaics as well, since the range for all industries is 10–30 percent and the value for the semiconductor industry is roughly 30 percent (ECN, 1999a). Here it is assumed that the learning rate stays at 20 percent—and that this rate applies to the total system price, not just to the module price.

In 1998 cumulative sales were roughly 800 megawatts. Production was about 150 megawatts. At growth of 15 percent a year (the average over the past 15 years; IEA PVPS, 1998), annual sales will double every five years—to about 3 gigawatts a year in 2020, when cumulative sales would be 25 gigawatts. As a result prices will have fallen in 2020 to a third of the 1998 level. With far more optimistic growth of 25 percent a year, annual sales would be 20 gigawatts a year in 2020, and cumulative sales 100 gigawatts. Prices will then have fallen to a fifth of the 1998 level.

Table 7.13 gives an overview of the cost estimates using a learning curve approach, for a learning rate of 20 percent (historic value). Results for a low learning rate of 10 percent are given for comparison. The projections using a learning curve approach show a somewhat slower decrease than those based on evaluations of photovoltaic production technologies. Note, however, that new technologies based on the use of thin-film solar cells can follow a different (lower) learning curve than the sum of all technologies.

Photovoltaic electricity costs. Electricity costs are determined by turnkey system costs, economic lifetime (depreciation period), interest rates, operation and maintenance costs (including possible replacement of components), electricity yields of the system (a function of insolation and thus of geographic location), insurance costs, and so on (table 7.14).

Implementation issues

Since the cost of photovoltaic electricity is now well above that of electricity from the grid, photovoltaics are implemented through two distinct paths. One is market development of commercial high-value applications. The second is stimulating the installation of grid-connected systems. Both paths are generally supported through government and international aid programs.

The first path deals mainly with standalone photovoltaic systems and (more recently but to less extent) with small grid-connected systems for private use. The photovoltaics industry has survived the past decades by actively developing niche markets in telecommunication, leisure, lighting, signalling, water-pumping, and rural electrification. The rural market is now being actively pursued as potentially huge, since an estimated 2 billion people in developing countries do not have access to a grid (see chapter 10).

Photovoltaics are often a viable alternative for bringing small amounts of electricity (less than 1 kilowatt-hour a day) to end users. More than 300,000 solar home systems (typically 50 watts) have been installed over the past 10 years, only a very modest step towards true large-scale use (Böer, 1998). In addition a large number of even smaller systems has been sold. This rural market cannot be judged by the total peak power of the systems (300,000 x 50 watts = 15 megawatts). Even if all 2 billion people were to own a 100 watt photovoltaic system, this would contribute less than 1 exajoule of electricity to the world's energy consumption. Instead, it is the large number of people involved that is significant—and even more that photovoltaics provide light, radio, television, and other important services to them.

A major barrier for rapid growth and very widespread use is the lack (in most countries) of properly developed financing schemes and the infrastructure for distribution, after-sales service, and so on. Financing is essential because few of those 2 billion people can pay cash of $400 for a system. But some can pay a smaller amount, or even a monthly rate of a few dollars up to tens of dollars. This widely acknowledged problem has two solutions. The first is the full commercial development of very small photovoltaic systems to meet basic needs and be paid for in cash (mainly photovoltaic lanterns and other lighting systems in the range of 5–20 watts). The second is financing schemes using a down payment and monthly fees of roughly $5–20 a lease, or fee-for-service (Böer, 1998).

For grid-connected systems it is important to distinguish between small and medium-sized decentralised systems (typically 500 watts to 1 megawatt) integrated in the built environment and large ground-based, central systems (typically greater than 1 megawatt). Decentralised integrated systems have some advantages over central ground-based ones. Their balance of system costs are generally lower. And they have more technical and non-technical possibilities to increase their competitiveness.

Photovoltaic market development through government programs in industrialised countries (IEA PVPV, 1998) applies mainly to systems integrated in the built environment. The aim of these programs is to boost the development and application of photovoltaic technology as an essential step towards future large-scale use. They provide market volume to the photovoltaics industry to achieve economies of scale and experience with a completely new

TABLE 7.13. POSSIBLE EVOLUTION OF TYPICAL COSTS OF GRID-CONNECTED PHOTOVOLTAIC SYSTEMS USING A LEARNING CURVE (APPROACH 2)

	1998	Medium term (2010)		Long term (2020)	
Average annual market growth rate (percent)	**15 (1983–98)**	**15**	**25**	**15**	**25**
Annual sales (gigawatts)	0.15	0.8	2	3	20
Cumulative sales (gigawatts)	0.8	6	11	25	100
Turnkey system price (1998 dollars per watt) at a learning rate of 20 percent	5–10	2.7–5.3	2.2–4.3	1.7–3.3	1 –2
Turnkey system price (1998 dollars per watt) at a learning rate of 10 percent	5–10	3.7–7.4	3.4–6.8	3.0–5.9	2.4–4.8

TABLE 7.14 ELECTRICITY COST AS A FUNCTION OF COST, ECONOMIC LIFETIME, AND ELECTRICITY YIELD OF PHOTOVOLTAIC SYSTEMS (DOLLARS A KILOWATT-HOUR)

Turnkey system cost (dollars a watt)	Economic lifetime (years)	Electricity yield (kilowatt-hours a year per kilowatt of installed capacity)	
		750	1,500
5 (lower limit 1998)	10	1.00–1.22	0.51–0.61
	25	0.61–0.87	0.31–0.44
1 (long term)	10	0.12–0.24	0.10–0.12
	25	0.12–0.17	0.06–0.09

Note: Operation and maintenance and insurance costs are 2 percent of the annual system cost. The interest rate is 5–10 percent.

way of sustainable (decentralised) electricity generation. Clearly, this policy-driven market depends on public support and high expectations for photovoltaics as a major electricity source for the future.

BOX 7.6 SELECTED NATIONAL AND INTERNATIONAL PHOTOVOLTAIC PROGRAMMES

Japan. In 1994 the Japanese government adopted the New Energy Introduction Outline, with targets for renewable energy technologies, including photovoltaics. The aim is to install 400 megawatts of (mainly residential grid-connected) photovoltaic systems by 2000 and 4,600 megawatts by 2010 (Luchi, 1998). The program is based on gradually decreasing subsidies (starting at 50 percent) and net metering.

United States. The Million Solar Roofs program aims to install 1,000,000 solar hot water systems and photovoltaic systems by 2010 (IEA PVPS, 1998; Böer, 1998). The trend is from demonstrations and tests towards market-centred projects with funding primarily from the private sector. The program works by creating partnerships between communities, federal agencies, and the Department of Energy (Rannels, 1998).

Germany. The 100,000 Roofs program (300–350 megawatts in 2005) is dedicated to grid-connected photovoltaic systems. Private investments in photovoltaics are stimulated by interest-free loans and a subsidy of 12.5 percent (Photon, 1999b). In addition, the government decided recently to pay nearly 1 deutsche mark a kilowatt-hour to owners of photovoltaic systems, financed by a small increase of electricity rates.

Italy. The 10,000 Rooftops program aims to install 50 megawatts by around 2005 (Garrozzo and Causi, 1998). With a focus on building small- and medium-sized integrated, grid-connected photovoltaic systems, funding may be mixed public (75 percent) and private (25 percent).

European Union. The target for photovoltaics is an installed capacity of 3 gigawatts by 2010. This has been translated into a Million Roofs program to install 500,000 grid-connected photovoltaic systems on roofs and facades in the Union and to export another 500,000 village systems for decentralised electrification in developing countries (EC, 1997; EC, 1999; IEA PVPS, 1998).

Indonesia. In 1998 the installed capacity of photovoltaic systems in Indonesia was 5 megawatts. A new strategy has been developed to enhance the use of renewable energy technologies, especially photovoltaics. Some characteristics of this strategy are: establish renewable energy non-governmental organisations, prepare renewable energy product standards, run demonstration projects in partnership with the private sector, provide training, disseminate information, strengthen international cooperation, and institute policy development and regulation.

India. With a total installed capacity of about 40 megawatts of photovoltaic systems, India has among the world's largest national programs in photovoltaics. The five-year national plan 1997–2002 envisages a deployment of 58 megawatts in addition to the 28 megawatts installed as of 1997. Exports of 12 megawatts are also foreseen. Government-sponsored programs include installing solar lanterns and other lighting systems—and electrifying villages and grid-connected power plants. Subsidies are available to rural users (Sastry, 1999).

South Africa. Shell Renewables Ltd. and Eskom are investing $30 million in rural solar power development in South Africa from 1999 until 2001. This venture should provide standalone photovoltaic units to about 50,000 homes presently without electricity at a cost of about $8 a month (see chapter 10).

Kenya. Kenya has a high penetration rate of household photovoltaic systems. In 1999 more than 80,000 systems were in place and annual sales are about 20,000 systems. The market operates without significant external aid or support (see chapter 10).

World Bank. The World Bank has become very active in developing financial schemes and programs for rural electrification in developing countries (Photon, 1999a). An example is the photovoltaic Market Transformation Initiative. The Bank's activities, fully integrated on a national level, mainly aim at removing barriers and building capacity. Generally, the approach is not to stimulate photovoltaics through subsidies for system hardware, but to facilitate commercial operations fitted to the local circumstances.

A variety of instruments can achieve a self-sustained market: rate-based measures (favourable feed-in tariffs), fiscal measures, investment subsidies, soft loans, building codes. Another instrument is the removal of barriers related, say, to building design and material use. In addition to these incentives, the added value of photovoltaics—like aesthetics in building integration, combining electricity generation and light transmission, and generating part or all of one's own electricity consumption—are used in marketing photovoltaics. Green electricity and green certificates for the use of renewables are also expected to be important in the further development of a self-sustained market for grid-connected systems. They enable selling electricity from photovoltaics (or other renewables) to environmentally conscious electricity consumers.

Several countries have set targets or formulated programs for renewable energy technologies, specifically solar (box 7.6). In countries with a well-developed electricity infrastructure, the long-term aim is to achieve a substantial contribution to the electricity generation from solar energy. In developing countries and countries with a less-developed electricity infrastructure, efforts are focused on the large-scale implementation of smaller standalone solar photovoltaic systems. In these cases the dissemination of solar energy is a tool for social and economic development.

Space-based solar energy

A very different approach to exploiting solar energy is to capture it in space and convey it to the Earth by wireless transmission. Unlike terrestrial capture of solar energy, a space-based system would not be limited by the vagaries of the day-night cycle and adverse weather—and so could provide baseload electricity (Glaser and others, 1997).

In space the maximum irradiance (power density) is much higher than on Earth—around 1,360 watts per square metre—and is nearly constant. This energy can be captured and converted to electricity just as it can on Earth, as is done routinely to power spacecraft. The elements of such a space-based solar energy system would include:

- Satellites in geosynchronous or other orbits designed as large solar collectors.
- Power conditioning and conversion components to turn the electricity generated by the photovoltaic arrays into radio frequency form.
- Transmitting antennas that form one or more beams directed from the satellites to the Earth.
- Receiving antennas on Earth that collect the incoming radio frequency energy and convert it into useful electricity. Such a device is called a rectenna (for rectifying receiving antenna). The power yield from typical rectennas at low to middle latitudes would be on the order of 30 megawatts per square kilometre.
- Power conditioning components to convert the direct current output from the rectenna to alternating current for local use.

As with any solar source, space-based energy would not contribute

Photovoltaics are often a viable alternative for bringing small amounts of electricity (less than 1 kilowatt-hour a day) to end users.

to greenhouse gas emissions during operation. The high launch rate required to place a space-based energy system could affect the Earth's atmosphere, however. The effects of power transmission to the ground need to be assessed for at least three factors: influences on the atmosphere (particularly the ionosphere on the way down), inference between the wireless power transmission and communications or electronic equipment, and the effects of the transmitted beam on life forms. Estimates and some experiments indicate that these effects might be small.

Very preliminary estimates suggest that a cost target of $0.05 per kilowatt-hour may ultimately be achievable for a mature space-based solar energy system (Mankins, 1998). But several important issues must be addressed:

- A number of key technologies require maturation.
- The cost of access to space must be substantially lowered.
- Safety and environmental concerns must be resolved.
- Optimal designs for space-based solar systems need to be established.
- Orbital slots for collecting platforms and frequencies for power transmission need to be obtained.

Conclusion

- Since 1983 the average growth rate of photovoltaic module shipments has been 15 percent a year. In 1998 the production was 150 megawatts, and in 1999, about 200 megawatts. In 1998 the cumulative production was around 800 megawatts, with the operating capacity probably about 500 megawatts, perhaps 600 megawatts. The growth of operating photovoltaic capacity in the last five years can be estimated at roughly 30 percent a year.
- Since 1975 the learning rate (cost reduction as function of cumulative production) has been roughly 20 percent. In 1998 turnkey costs of grid-connected photovoltaic systems were $5–10 a watt. In the future these costs may come down to about $1 a watt.
- Today photovoltaics generally cannot compete with conventional power plants in grid-connected applications. Photovoltaic electricity production costs are about $0.3–1.5 a kilowatt-hour, depending on solar insolation, turnkey costs, depreciation periods, and interest rates. Under favourable conditions and at favourable sites, the lowest cost figure may come down to $0.05-0.06 a kilowatt-hour.
- It remains uncertain whether and when photovoltaics will compete with fossil fuels on a large scale. This mainly depends on the development of photovoltaics, on the price development of coal and natural gas, and on possibilities for (or policies on) carbon dioxide removal at low cost.
- Supplying less than 1 percent of the world's energy consumption, photovoltaic systems can play a major role in rural electrification by reaching many of the 2 billion people in developing countries who do not have access to electricity.
- There appear to be no invincible technical problems for solar energy to contribute much to the world's energy supply. What matters are policy developments and the market position of fossil fuels and other energy sources.

Solar thermal electricity

Solar radiation can produce high-temperature heat, which can generate electricity. The most important solar thermal technologies to produce electricity—concentrating—use direct irradiation. Low cloud areas with little scattered radiation, such as deserts, are considered most suitable for direct-beam-only collectors. Thus the primary market for concentrating solar thermal electric technologies is in sunnier regions, particularly in warm temperate, sub-tropical, or desert areas. About 1 percent of the world's desert area used by solar thermal power plants would be sufficient to generate today's world electricity demand. Here we will assess the current status and future development of solar thermal electricity (STE) technologies.

The potential of solar thermal electricity

STE is probably 20 years behind wind power in market exploitation. In 1998 operating STE capacity was about 400 megawatts of electricity, with annual electricity output of nearly 1 terawatt-hour. New projects in mind mount to a maximum of 500 megawatts of electricity, and it is probable that 2,000 megawatts of installed capacity will not be reached until 2010 (the capacity wind reached in 1990). Because STE costs are dropping rapidly towards levels similar to those obtained by wind, STE may grow in a manner somewhat similar to wind. If the growth rate is 20–25 percent after 2010, this installed STE capacity would be 12,000–18,000 megawatts of electricity by 2020. If annual growth rate then averages 15 percent a year, the result would be 800–1,200 gigawatts of electricity by 2050. The Cost Reduction Study for Solar Thermal Power Plants, prepared for the World Bank in early 1999 (Enermodal, 1999), concludes that the large potential market of STE could reach an annual installation rate of 2,000 megawatts of electricity. In the foregoing scenario this rate is reached between 2015 and 2020. Advanced low-cost STE systems are likely to offer energy output at an annual capacity factor of 0.22 or more. So, the contribution of STE would be about 24–36 terawatt-hours of electricity by 2020 and 1,600–2,400 terawatt-hours by 2050.

Solar thermal electricity market developments

STE technologies can meet the requirements of two major electric power markets: large-scale dispatchable markets comprising grid-connected peaking and baseload power, and rapidly expanding distributed markets including both on-grid and remote applications.

Dispatchable power markets. Using storage and hybridisation capabilities (integration of STE with fossil fuel power plants), dispatchable solar thermal electric technologies can address this market. Currently offering the lowest-cost, highest-value solar electricity available, they have the potential to be economically competitive with fossil energy in the longer term. With continuing development success and early implementation opportunities, the electricity production cost of dispatchable STE systems is expected to drop from $0.12–0.18 a kilowatt-hour today to about $0.08–0.14 a kilowatt-hour in 2005 and to $0.04–0.10 a kilowatt-hour thereafter.

In this market there is a huge existing global capacity of fossil fuel plant, much of it coal, available for low solar-fraction retrofit as a transition strategy. Coal-fired plants tend to be much larger individually than solar thermal standalone plants (600–1,200 megawatts of electricity compared with 5–80 megawatts), and usable land around coal-fired plants is restricted. Any solar retrofit to a typical coal-fired plant will supply only a small percentage of its total electricity output. But around the world, there are hundreds of such fossil fuel plants in good insolation areas, many with sufficient adjacent land area to accommodate a solar field of the size of the current largest STE units of about 80 megawatts. This market could account for a large fraction of the 12,000–18,000 megawatts by 2020 in the scenario above.

Distributed power markets. The majority of these applications are for remote power, such as water pumping and village electrification, with no utility grid. In these applications, diesel engine generators are the primary current competition. The STE technology appropriate for smaller distributed applications is the dish/engine system. Each dish/engine module (10–50 kilowatts of electricity) is an independent power system designed for automatic start-up and unattended operation. Multiple dish/engine systems can be installed at a single site to provide as much power as required, and the system can readily be expanded with additional modules to accommodate future load growth. The systems can be designed for solar-only applications, easily hybridised with fossil fuels to allow power production without sunlight, or deployed with battery systems to store energy for later use.

The high value of distributed power (more than $0.50 a kilowatt-hour for some remote applications) provides opportunities for commercial deployment early in the technology development. The technology enhancements needed to achieve high reliability and reduce operation and maintenance costs are understood. With continuing development, the electricity production costs of distributed STE system are expected to drop from $0.20–0.40 a kilowatt-hour today to about $0.12–0.20 a kilowatt-hour in 2005 and to $0.05–0.10 a kilowatt-hour in the long run.

STE projects, ranging from about 10 kilowatts to 80 megawatts of electricity, have been realised or are being developed in Australia, Egypt, Greece, India, Iran, Jordan, Mexico, Morocco, Spain, and the United States (box 7.7).

Market entry strategy. Three phases can be distinguished in an STE market entry strategy:

- *Solar field additions.* Small solar fields can be integrated into combined cycle and coal or fuel oil-fired power plants for $700–1,500 per kilowatt installed.
- *Increased solar share.* With increasing fossil fuel prices or compensation premiums for carbon dioxide avoidance as well as solar field cost reductions, the share of solar can be increased to about 50 percent in solar-fossil hybrid power stations.
- *Thermal energy storage.* With further improvement in the cost-benefit ratio of STE, thermal energy storage will further substitute for the need of a fossil back-up fuel source. In the long run, baseload operated solar thermal power plants without any fossil fuel addition are in principle possible, and clean bio-energy back-up is also feasible.

Figure 7.6 presents an outlook on the market introduction of STE technologies and the associated reduction in electricity generation costs as presented by SunLab (1999).

BOX 7.7. COMMERCIAL SOLAR THERMAL ELECTRICITY DEVELOPMENTS NOW UNDER WAY

Australia. Under the Australian Greenhouse Office (AGO) Renewable Energy Showcase Programme, a 13 megawatt-thermal compact linear fresnel reflector (CLFR) demonstration unit will be installed in 2001, retrofitted to an existing 1,400 megawatts-electric coal-fired plant in Queensland (Burbridge and others, 2000). It is expected to offer the solar electricity from this first commercial project as green power at a price below $0.09 a kilowatt-hour. A 2 megawatts-electric demonstration unit, using paraboloidal dish technology, has also been announced for installation in 2001, retrofitted to a gas-fired steam generating plant (Luzzi, 2000).

Greece. On the island of Crete, the private venture capital fund Solar Millennium—together with Greek and European industrial partners—has established the first solar thermal project company (THESEUS S.A.) and submitted an application for licensing a 52 megawatt-thermal solar thermal power plant with 300,000 square metres of parabolic trough solar field.

Spain. New incentive premiums for the generation of renewable electricity in 1999 caused Spanish companies such as Abengoa, Gamesa, and Ghersa to engage in solar thermal technologies and to establish various project companies (Osuna and others, 2000).

United States. Green electricity and renewable portfolio policies of various states have revived the interest of such industrial firms as Bechtel, Boeing, and Dukesolar in the further development of STE technologies.

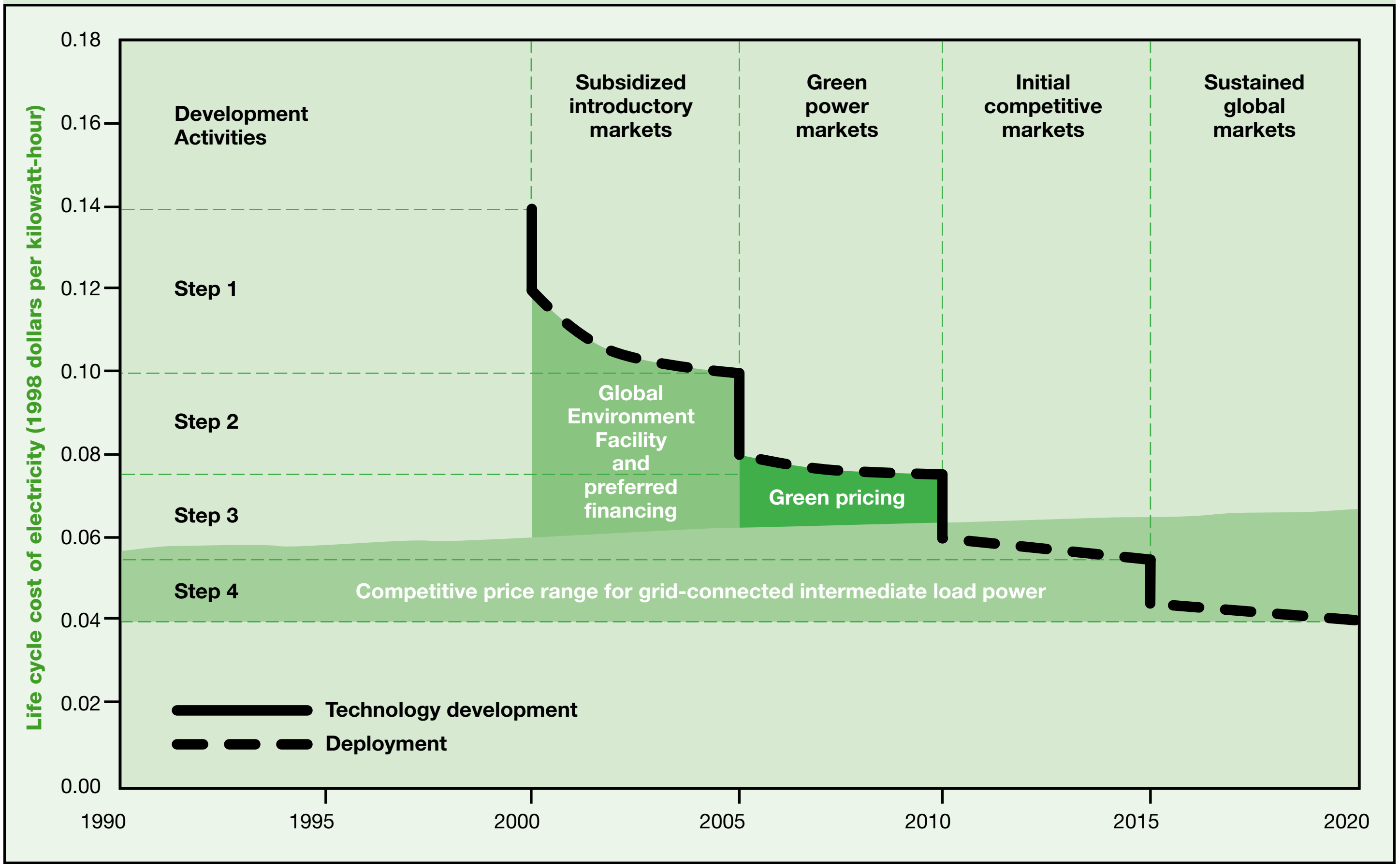
Global Environment Facility. In 1999 the Global Environmental Facility approved grants for the first solar thermal projects in Egypt, India, Mexico, and Morocco—about $200 million in total. The proposed Indian plant uses integrated gas combined cycle and solar thermal (Garg, 2000).

Solar thermal electricity technologies

Five distinct solar thermal electric conversion concepts are available, each with different operating and commercial features. Two non-concentrating technologies—solar chimney and solar pond—are not included in this brief description of emerging solar thermal power concepts, because they lack significantly sized pilot and demonstration test facilities.

All concentrating solar power technologies rely on four basic key elements: collector/concentrator, receiver, transport/storage, and power conversion. The collector/concentrator captures and concentrates solar radiation, which is then delivered to the receiver. The receiver absorbs the concentrated sunlight, transferring its heat energy to a working fluid. The transport/storage system passes the fluid from the receiver to the power conversion system. In some solar thermal plants a portion of the thermal energy is stored for later use. As solar thermal power conversion systems, Rankine, Brayton, Combined, and Stirling cycles have been successfully demonstrated.

FIGURE 7.6 MARKET INTRODUCTION OF SOLAR THERMAL ELECTRICITY TECHNOLOGIES WITH INITIAL SUBSIDIES AND GREEN POWER TARIFFS, 1990–2020



Source: SunLab, 1999.

An inherent advantage of STE technologies is their unique ability to be integrated with conventional thermal plants. All of them can be integrated as a solar boiler into conventional thermal cycles, in parallel with a fossil-fuelled boiler. They can thus be provided with thermal storage or fossil fuel back-up firm capacity without the need for separate back-up power plants and without stochastic perturbations of the grid (figure 7.7). The potential availability of storage and ability to share generation facilities with clean biomass suggest a future ability to provide a 100 percent replacement for high capacity factor fossil fuel plant when needed.

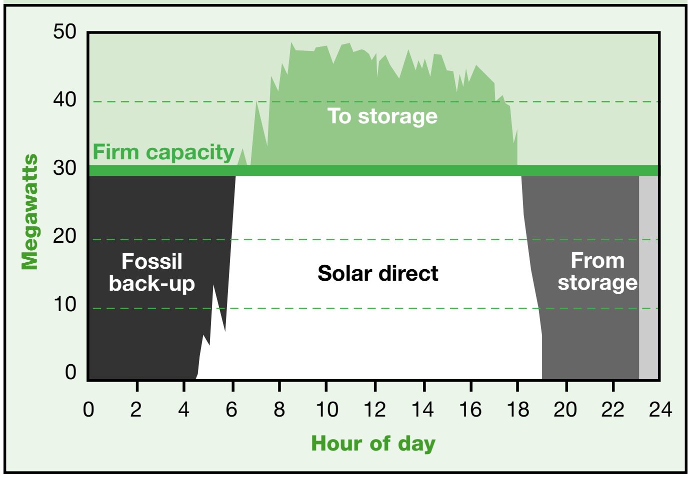
Parabolic trough systems. The parabolic trough (solar farm) consists of long parallel rows of identical concentrator modules, typically using trough-shaped glass mirrors. Tracking the sun from east to west by rotation on one axis, the trough collector concentrates the direct solar radiation onto an absorber pipe located along its focal line. A heat transfer medium, typically oil at temperatures up to 400 degrees Celsius, is circulated through the pipes. The hot oil converts water to steam, driving the steam turbine generator of a conventional power block.

With 354 megawatts-electric of parabolic trough solar electric generating systems connected to the grid in southern California since the mid-1980s, parabolic troughs are the most mature STE technology (Pilkington, 1996). There are more than 100 plant-years of experience from the nine operating plants. The plants range in size from 14–80 megawatts of electricity. Until the end of 1998, 8 terawatt-hours of solar electrical energy had been fed into the Californian grid, resulting in sales revenues of more than $1,000 million. The technology is under active development and refinement to improve its performance and reduce production costs.

Central receiver/power tower. The solar central receiver or power tower is surrounded by a large array of two-axis tracking mirrors—termed heliostats—reflecting direct solar radiation onto a fixed receiver located on the top of the tower. Within the receiver, a fluid transfers the absorbed solar heat to the power block where it is used to heat a steam generator. Water, air, liquid metal, and molten salt have been tested as fluids.

Advanced high-temperature power tower concepts are now under investigation, heating pressurised air to more than 1,000 degrees Celsius to feed it into the gas turbines of modern combined cycles. In Barstow, California, a 10 megawatts-electric pilot plant

FIGURE 7.7. WITH MINIMAL FOSSIL BACK-UP AND THERMAL ENERGY STORAGE, SOLAR CAPACITY IS TRANSFORMED INTO FIRM CAPACITY



Source: Geyer, 1999.

(Solar One) operated with steam from 1982–88. After modification of the complete plant in 1996, it operated as Solar Two for a few thousand hours, with molten salt as the heat-transfer and energy-storage medium, delivering power to the electricity grid on a regular basis (Pacheco and others, 2000). The net solar-electric conversion efficiency was 8 percent. Solar Two has demonstrated, through storage, the feasibility of delivering utility-scale solar power to the grid 24 hours a day, if necessary (Kolb, 1998). In parallel, European activities have demonstrated the volumetric air receiver concept, where the solar energy is absorbed on fine-mesh screens and immediately transferred to air as the working fluid (Buck and others, 2000).

Dish/engine power plants. Parabolic dish systems consist of a parabolic-shaped point focus concentrator in the form of a dish that reflects solar radiation onto a receiver mounted at the focal point. These concentrators are mounted on a structure with a two-axis tracking system to follow the sun. The collected heat is often used directly by a heat engine, mounted on the receiver. Stirling and Brayton cycle engines are currently favoured for decentralised power conversion. Central Rankine cycles are being studied for large fields of such dishes where the receiver does not contain a heat engine.

Several dish/engine prototypes have operated successfully in the last 10 years, including 7–25 kilowatts-electric units developed in the United States. But there has not yet been a large-scale deployment. In Spain six units with a 9–10 kilowatts-electric rating are operating successfully. Australia has demonstrated a 400 square metre, 10 kilowatts-electric ‘big dish’ at the Australian National University in Canberra (Luzzi, 2000). Work is proceeding to develop a dish plant of 2–3 megawatts- electric attached to an existing fossil fuel power plant.

Advanced systems under development. Compact linear fresnel reflector (CLFR) technology has recently been developed at the University of Sydney in Australia. Individual reflectors have the option of directing reflected solar radiation to at least two towers. This additional variable in reflector orientation provides the means for much more densely packed arrays. The CLFR concept, intended to reduce costs in all elements of the solar thermal array, includes many additional features that enhance system cost and performance. The technology aims only at temperatures suitable for steam boilers and pre-heaters, with the view that superheating is a minor input and can be done by other fuels.

Fuels. Long-term research is under way in Australia, Germany, Israel, Switzerland, and elsewhere to produce solar fuels for a range of uses, including fuel cells for electricity production. This work is targeted towards the thermochemical conversion of solar energy into chemical energy carriers (hydrogen, synthesis gas, metals).

Economic aspects

The Cost Reduction Study for Solar Thermal Power Plants (Enermodal, 1999) has assessed the current and future cost competitiveness of STE with conventional power systems for two STE technologies: the parabolic trough and the molten salt central receiver system. Two approaches were used to assess the future cost performance of these technologies: an engineering approach based on known technical improvements and cost reductions from commercialisation, and a learning (experience) curve approach. The two approaches yielded similar results.

Costs per kilowatt of trough plants are expected to fall from \$3,000–3,500 a kilowatt in the near term (for a 30 megawatts-electric plant) to \$2,000–2,500 a kilowatt in the long term (for a 200 megawatts-electric plant). For central receiver systems these figures are \$4,200–5,000 a kilowatt in the near term and \$1,600–1,900 a kilowatt in the long term. The attainable net solar-to-electric conversion efficiencies of these systems are expected to be 13–16 percent in the near term and 18–20 percent in the long term. Operation and maintenance costs can decrease from about \$0.025 a kilowatt-hour in the near term to about \$0.005 a kilowatt-hour in the long term.

If the cost of electricity from conventional power plants stays constant over the next 20 years, the solar levelised energy cost (LEC) can be calculated to fall to less than half of current values—from \$0.14–0.18 a kilowatt-hour to \$0.04–0.06 a kilowatt-hour. At this cost, the potential for STE power plants to compete with Rankine cycle plants (coal, gas, or oil fired) can be promising. The solar LEC for the tower is calculated to be less than for the trough because of the use of thermal storage. If troughs were equipped with storage as well, the same advantage would probably be found. It can thus be concluded that 24-hour power does not increase the total generating costs. If a credit of \$25–40 a tonne were included for reduced carbon dioxide emissions, STE power may have an even lower LEC than coal-fired Rankine plants.

Environmental and social aspects

Carbon dioxide emission savings. A solar boiler can supply 2,000 to 2,500 full load hours per year to a steam cycle. With STE technologies, each square meter of solar field can produce up to 1,200 kilowatt-hours of thermal energy a year—or up to 500 kilowatt-hours of electricity a year. Taking into account a thermal plant carbon dioxide emissions of 0.4–0.8 kilograms a kilowatt-hour electric, there results a cumulative saving of up to 5–10 tonnes of carbon dioxide per square metre of STE system over its 25-year lifetime (Pilkington, 1996).

The easiest and most direct application of solar energy is the direct conversion of sunlight into low-temperature heat.

Impact on fossil fuels consumption. The embodied energy of a STE plant is recovered after less than 1.5 years of plant operation (Lenzen, 1999). STE systems can preserve fossil energy or biomass resources. Taking into account an average conventional thermal power plant efficiency of 40 percent, there results a cumulative saving of about 2.5 tonnes of coal per square metre of solar field over its 25-year lifetime.

Land use. Land use is sometimes cited as a concern with renewables. If renewables are to contribute to energy production on a global scale, sufficient areas have to be available in suitable locations. Most solar thermal power plants need about 1 square kilometre of area for 60 megawatts of electricity capacity, although STE technologies like CLFR (see above) might reduce this by a factor or 3 or so (Mills and Morrison, 2000a, b).

Domestic supply of equipment and materials. The higher up-front cost of solar thermal power stations results from the additional investment into the STE equipment and erection. Most of this equipment and most of the construction materials required can be produced domestically. The evaluation of the domestic supply capability of selected countries indicates national supply shares ranging from 40 percent to more than 50 percent of the total project value. This supply share can be increased for subsequent projects (Pilkington, 1996).

Labour requirements. The erection and operation of the nine STE power plants in California indicate current labour requirements. The last 80 megawatts-electric plants showed that during the two-year construction period, there is a peak of about 1,000 jobs. Operation of the plant requires about 50 permanent qualified jobs (Pilkington, 1996).

Conclusion

- In the sunbelt of the world, solar thermal power is one of the candidates to provide a significant share of renewable clean energy needed in the future.
- STE is now ready for more widespread application if we start more intensified market penetration immediately; its application is not strongly restricted by land area or resource limitations.
- The STE technology appropriate for smaller remote power production is the dish/engine power plant. For grid-connected applications, technologies such as the parabolic trough system and the central receiver/power tower are applied.
- The installed STE capacity, now about 400 megawatts of electricity, may grow to 2,000 megawatts of electricity in 2010—and to 12,000–18,000 megawatts of electricity in 2020. An annual growth rate of 15 percent after 2020 would yield 1,600–2,400 terawatt-hours a year by 2050.
- Small solar fields can be integrated into fossil fuel power plants at relatively low costs. With improvement of the cost-benefit ratio of STE, the solar share in hybrid solar/fossil power plants may increase to about 50 percent. Thermal energy storage will be able to further substitute for the need for a fossil back-up fuel. In the long run, baseload-operated solar thermal power plants without any fossil fuel addition are now technically proven.
- STE is the lowest-cost solar electricity in the world, promising cost competitiveness with fossil fuel plants in the future—especially if assisted by environmental credits. Electricity production costs of grid-connected STE systems may come down from $0.12–0.18 a kilowatt-hour today to $0.04–0.10 a kilowatt-hour in the long term. In remote areas, the production costs of distributed systems may come down from $0.20–0.40 a kilowatt-hour today to $0.05–0.10 a kilowatt-hour in the long term.

Low-temperature solar energy

The easiest and most direct application of solar energy is the direct conversion of sunlight into low-temperature heat—up to a temperature of 100 degrees Celsius. In general, two classes of technologies can be distinguished: passive and active solar energy conversion. With active conversion there is always a solar collector, and the heat is transported to the process by a medium. With passive conversion the conversion takes place in the process, so no active components are used.

In this section the main focus is on active conversion, for which a broad range of technologies is available. The best known is the solar domestic hot water system. Another technology in the building sector is the solar space heating system. Such a system can be sized for single houses or for collective buildings and district heating. Similar technologies can be applied in the industrial and agricultural sector for low-temperature heating and drying applications. Heating using solar energy can also be achieved by heat pumps. Finally, there are technologies to use solar energy for cooling and cooking purposes.

Low-temperature solar energy potential and market developments

The world's commercial low-temperature heat consumption can be estimated at about 50 exajoules a year for space heating and at about 10 exajoules a year for hot water production. Low- and medium-temperature heat (up to 200 degrees Celsius) is also used as process heat, in total about 40 exajoules a year. Almost any low-and medium-temperature heat demand can be met at least partially with solar energy. One of the drawbacks for this application is the mismatch between availability of sunlight and demand for heating. Therefore nearly any solar heating system contains a storage unit.

The solar domestic hot water system (SDHW) is the most important application for low-temperature solar heat at this moment. In 1994 some 7 million SDHWs had been installed world-wide. In 1994 the total installed collector area of SDHWs and other solar energy systems was about 22 million square metres (Morrison, 1999) and in 1998 about 30 million square metres. This can be expressed as an installed capacity of around 18,000 megawatts. The total amount of heat generated by these solar energy systems can be estimated roughly at 50 petajoules a year. This is only 0.5 percent of the potential of around 10 exajoules a year. Table 7.15 provides an overview of the annually produced and total installed glazed collector area.

In Europe the market rapidly expanded after 1994. In 1996 about 700,000 square metres were produced, mainly in Germany (330,000 square metres) and Austria (230,000 square metres). The European Solar Industry Federation expects annual growth of around 20 percent (ESIF, 1996). In 1998 sales in Europe were probably on the order of 1 million square metres. In the United States the market has declined—the amount of collector area sold in SDHW systems decreased from 1.1 million square metres in 1984 to around 80,000 square metres in 1998 (Morrison, 1999). The market collapsed in 1986 because the federal R&D funding and tax credits ended abruptly. In China production is increasing rapidly. In Japan the market is increasing after a collapse in 1987 (ESIF, 1996). For different regions, growth of 10–25 percent a year is foreseen. In 2010 the installed collector area could be 150 million square metres.

TABLE 7.15. MAJOR SOLAR COLLECTOR MARKETS, 1994 (THOUSANDS OF SQUARE METRES)

Economy	Total glazed collector area installed	Glazed collector area produced
Australia	**1,400**	**140**
China	**1,500**	**500**
India	**500**	**50**
Israel	**2,800**	**300**
Japan	**7,000**	**500**
Taiwan, China	**200**	**90**
United States	**4,000**	**70**
Europe	**4,700**	**500**
Austria	400	125
Cyprus	600	30
France	260	18
Germany	690	140
Greece	2,000	120
Portugal	200	13
World	**~ 22,000**	**~ 2,200**

Source: Based on Morrison, 1999.

TABLE 7.16. CHARACTERISTICS OF SOLAR DOMESTIC HOT WATER SYSTEMS IN EUROPE

Feature	Northern Europe	Central Europe	Mediterranean
Collector area (square metres)	**3–6**	**3–5**	**2–4**
Storage capacity (litres)	**100–300**	**200–300**	**100–200**
Annual system performance (kilowatt-hours per square metre)	**300–450**	**400–550**	**500–650**
Installed system costs (dollars per square metre)	**400–1,000**	**400–1,000**	**300–600[a]**
Common system type	**Pump/ circulation**	**Pump/ circulation**	**Thermo-syphon**

a. In countries like Israel and Turkey this figure can be even lower.

Another important technology is the electric heat pump. Driven by electricity, this pump can withdraw heat from a heat source and raise the temperature to deliver the heat to a process (such as space heating). Tens of millions of appliances have been installed that can be operated as heat pumps, while most of them can also be operated as cooling devices (air conditioners). Whether the application of these machines results in net fuel savings depends on the local situation, taking into account aspects such as the performance of the heat pump, the reference situation, and characteristics of the electricity source. A lack of data makes it impossible to determine the net contribution of heat pumps to the energy supply.

Low-temperature solar energy technologies and systems

Solar domestic hot water systems. The solar domestic hot water system (SDHW) consists of three components: a solar collector panel, a storage tank, and a circulation system to transfer the heat from the panel to the store. SDHW systems for household range in size, because of differences in hot water demands and climate conditions. In general price/performance analysis will be made to size the solar hot water system and to investigate the optimum solar fraction (contribution of solar energy in energy demand). The results show a general dependence on the climate. The SDHW systems in Northern and Central Europe are designed to operate on a solar fraction of 50–65 percent. Subtropical climates generally achieve solar fractions of 80–100 percent. Table 7.16 indicates typical characteristics of applied systems in various climate zones in Europe.

Pump/circulation systems are generally used in climate zones with a serious frost and overheating danger. These systems either use the drain-back principle (the fluid drains from the collector if there is no solar contribution) or an antifreeze additive in the collector fluid. In countries with a warmer climate, natural circulation systems are mostly used. Almost all collectors installed are of the flat plate type. But in China in 1997 about 2 million evacuated tube collectors (about 150,000 square metres of collector area) were produced (Morrison, 1999). These are double-walled concentric glass tubes, of which the enclosed space is evacuated.

In regions with high solar irradiation, the use of SDHW systems may result in solar heat production costs ranging from $0.03–0.12 a kilowatt-hour. In regions with relatively low solar irradiation, the costs may range from $0.08–0.25 a kilowatt-hour. In many areas these costs can be competitive with electricity prices—but in most cases not with fossil fuel prices. Further cost reductions are therefore required.

- One approach is the use of complete prefabricated systems or kits, leaving no possibility to make changes in the system design, thus simplifying the installation work and reducing both the hardware and the installation cost.

- Another approach, in Northern Europe, is the development of solar thermal energy markets on a large scale, to reduce production, installation, and overhead costs. As demonstrated in the Netherlands, large projects can reduce the installed system price by 30–40 percent relative to the price of individually marketed systems.
- Cost reductions can also be achieved by further development of the technology (including integration of collector and storage unit). As a result of these approaches, solar heat production costs may come down 40–50 percent (TNO, 1992).

SDHW systems are commonly produced from metals (aluminium, copper, steel), glass and insulation materials. In most designs the systems can easily be separated into the constituent materials; all metals and glass can be recycled. The energy payback time of a SDHW system is now generally less than one year (van der Leun, 1994).

Large water heating systems. Solar thermal systems can provide heat and hot water for direct use or as pre-heated water to boilers that generate steam. Such large water heating systems find widespread use in swimming pools, hotels, hospitals, and homes for the elderly. Other markets are fertiliser and chemical factories, textile mills, dairies, and food processing units. Substantial quantities of fossil fuels or electricity can be saved through their use. But the installed collector area is rather low—around a tenth of the total installed area. It is especially low in the industrial sector, mainly because of low fossil fuel costs and relatively high economic payback times of solar systems. India provides tax benefits through accelerated depreciation on such commercial systems and also has a programme to provide soft loans to finance their installation. Within these systems about 400,000 square metres of collector area has been installed in India (TERI, 1996/97). The costs per kilowatt-hour of large water heating systems are now somewhat less than SDHW energy costs. And in the long term these costs can be reduced, probably about 25 percent, mainly by mass production.

Solar space heating. Total world space heating demand is estimated at 50 exajoules a year. In northern climates this demand can be more than 20 percent of total energy use. Mismatch between supply and demand limits the direct contribution of solar thermal energy to the space heating of a building to a maximum of 20 percent in these regions. If seasonal storage of heat is applied, solar fractions of up to 100 percent are achievable (Fisch, 1998). Space heating systems are available as water systems and as air heating systems, with air heating systems generally cheaper. Water-based systems are usually solar combi-systems that supply domestic hot water and space heating.

Seasonal storage has mainly been applied in demonstration projects, showing its technological feasibility. The technologies are divided into large and small systems. For large systems (storage for more than 250 houses) the insulation is not so important, and duct storage or aquifer storage is possible. For small systems storage of heat in an insulated tank is the only solution to date. More advanced concepts—such as chemical storage of heat—have been proven on a laboratory scale. Storage of cold from the winter to be used in the summer has proven to be profitable, if aquifers are available in the underground.

Passive solar energy use has become an attractive option for heating and cooling buildings because of the development of new materials and powerful simulation tools.

District heating. Solar energy can also be applied for district heating. Providing hot water and space heat, several of these systems, using a central collector area, have been realised in Denmark, Germany, and Sweden. They reach similar solar fractions as single house systems: 50 percent for hot water production and 15 percent for the total heat demand (hot water plus space heating). Some of these systems have been combined with a seasonal storage increasing the solar fraction to 80 percent for the total heat demand.

Heat pumps. Heat pumps can generate high-temperature heat from a low-temperature heat source. Working in the opposite direction the same appliance can also be used as a cooling device. In fact most heat pumps are air conditioners that are also suitable for heating purposes. Tens of millions of these appliances have been installed world-wide. In colder climates there is a market for heat pumps for heating only. In Europe in 1996 around 900,000 of these pumps were installed (Laue, 1999), and the market is growing at about 10 percent a year (Bouma, 1999).

Energy (mostly electricity) is needed to operate the heat pump. Typically the heat energy output is two to four times the electrical energy input. The low-temperature heat input can come directly or indirectly from the sun. For example, with ground-coupled heat pump systems, the surface can be seen as a cheap solar collector—and the ground beneath it as a storage system from which the low-temperature heat can be extracted. Today, however, most systems extract heat from the open air. Different systems have been tested using solar collectors as a heat source. Because heat pumps can work with low temperatures, the collectors can be cheap.

No general statement can be made about the contribution of heat pumps to savings in fossil fuel consumption and environmental emissions. But by further improving the performance of the heat pump and by using electricity from renewable sources (hydro, wind, photovoltaics), this contribution will be definitely positive.

Solar cooling. About 30 million air conditioners are sold each year (Nishimura, 1999). Cooling with solar heat seems an obvious application, because demand for cooling and supply of solar heat are in phase. The technologies available are absorption cooling, adsorption cooling, and desiccant cooling. A standard, single-effect absorption chiller can be driven with temperatures around 90 degrees Celsius. This can be generated with standard flat plate solar collectors. Different systems have been designed and tested, but their economics turned out to be poor. As a result this field of applications has been disregarded over the last 10 years. Recently some newer cooling cycles have become available, the solar collector performance has improved, and collector prices have gone down. So solar cooling may become a feasible option (Henning, 1999).

Solar cooking. About half the world's cooking uses firewood as the fuel, with the other half based on gas, kerosene, or electricity. In some regions cooking energy requirements place a great pressure on biomass resources while also causing considerable inconvenience and health effects to users in the collection and burning of biomass (see chapter 3). Considering that these regions also have significant levels of solar radiation, it would appear that cooking provides a significant and beneficial impact.

China and India are among several countries promoting the use of solar cookers. A simple box-type cooker and a parabolic concentrating type cooker are among the common models deployed. Efforts have also been made to develop solar cookers for institutional use. In India some 450,000 box type cookers have been installed. The world's largest solar cooking system—capable of preparing meals for 10,000 persons twice a day—was installed in 1999 in Taleti in Rajasthan, India (TERI, 1996/97; MNCES, 1999). In China some 100,000 concentrator-type cookers have been deployed (Wentzel, 1995).

Solar cooking devices have certain limitations and can only supplement, not replace conventional fuels. A home that uses a solar cooker regularly can save a third to a half of the conventional fuel that is used for cooking. The economic payback time is usually between 2–4 years. The large-scale use of solar cookers, however, will also require some adjustment by users.

Solar crop drying. The drying of agricultural products requires large quantities of low-temperature heat—in many cases, year round. Low-cost air-based solar collectors can provide this heat at collection efficiencies of 30–70 percent (Voskens and Carpenter, 1999). In Finland, Norway, and Switzerland hay drying is already an established technology. By 1998 more than 100,000 square metres of air collectors for drying purposes had been installed.

In developing countries 60–70 percent of grain production (as estimated by the Food and Agriculture Organisation) is retained at the farmer level, and crop drying is effected predominantly by exposure to direct sunlight (sun drying). In industrialised countries crops are typically dried in large fossil-fuelled drying systems, operating at relatively high temperatures with a high throughput of material. If a solar dryer is used in place of sun drying, there will not be any energy savings, but the solar dryer will achieve higher throughput of material, better quality of material, and lower loss of material (to pests or theft). Air-collector-type solar dryers have the most potential in replacing fuel-fired dryers for crops dried at temperatures less than 50 degrees Celsius (table 7.17).

TABLE 7.17. WORLD PRACTICAL POTENTIAL ESTIMATION FOR SOLAR CROP DRYING (PETAJOULES A YEAR)

Type of drying	Low	High
< 50 degrees Celsius	220	770
> 50 degrees Celsius	40	110
Sun dried	420	650
Total	**680**	**1,530**

Source: ESIF, 1996; Voskens and Carpenter, 1999.

The technology for solar crop drying is available, and its application can be economically viable. Market introduction of these technologies will thus be the next step, but that will require training and demonstration projects targeted at specific crops and specific potential users and regions.

Passive solar energy use. The application of passive solar principles can contribute significantly to the reduction of (active) energy demands for heating, cooling, lighting, and ventilating buildings. Some of these principles (Boyle, 1996) are :

- Be well insulated.
- Have a responsive, efficient heating system.
- Face south.
- Avoid overshading by other buildings.
- Be thermally massive.

The principles have to be considered in relation to the building design process, because they have a direct effect on the architectural appearance of the building, on the level of comfort (heat, cold, light, ventilation), and on people's experience of the building. Nowadays a number of techniques can diminish energy demands with passive means:

- *Low-emission double-glazed windows.* In cold climates these windows keep out the cold while allowing the solar radiation to pass. In summer the windows can be shaded, and heat is kept outside.
- *Low-cost opaque insulation material and high insulating building elements.* These elements can keep out the heat as well as the cold.
- *Transparent insulation material.* This material can be used to allow day-lighting while keeping out the cold or heat.
- *High-efficiency ventilation heat recovery.*
- *High-efficiency lighting systems and electrical appliances with automatic control.* These can bring down the internal heat gain, reducing the cooling load. Advanced daylight systems can lead to 40 percent reduction of the energy use for lighting purposes.

By carrying out detailed simulation studies, the energy demand of a building can be optimised, without affecting comfort (Hastings, 1994). It has been estimated that 13 percent of the heat demand of buildings is covered by passive solar energy use. For optimised buildings this fraction can go up to 30 percent without major investments (Brouwer and Bosselaar, 1999). Because of the development of better materials and powerful simulation models, passive use of solar energy is becoming the number one consideration for heating and cooling buildings.

Implementation issues

In many countries incentive programmes help to stimulate the further development and application of low-temperature solar energy systems, improving their performance and reducing economic and other barriers. In countries where government stimulation is lacking, it is often the economic attractiveness of the system or environmental conscience that motivates people to install these systems.

In many cases energy companies, especially utilities, have stimulated the use of solar thermal energy. Motivated by environmental action programs, demand-side management programs, or a desire to diversify and serve new markets, these companies have taken over a significant part of the effort to get the solar water systems to the market. They support these projects by active marketing, by financial contributions, or by offering the possibility to rent or lease a system (IEA Caddet, 1998).

Conclusion

- Low-temperature solar thermal technologies can contribute many exajoules to the annual heat demand. Today this contribution is limited to about 50 petajoules a year (excluding heat pumps and passive solar energy use).
- World-wide, about 7 million solar hot water systems, mainly SDHW systems, have been installed. In many regions their dissemination strongly depends on governmental policy, mainly because of the relatively high heat-production costs ($0.03–0.20 a kilowatt hour). They can, however, compete with electric hot water systems.
- The costs of installed solar hot water systems in moderate climate zones may be reduced 25–50 percent by further technology development and/or mass production and installation.
- Active solar systems for space heating with seasonal storage are mainly in a demonstration phase.
- Passive solar energy use has become an attractive option in heating and cooling buildings, because of the development of new materials and powerful simulation tools.
- Electric heat pumps for space heating are especially attractive in countries where electricity is produced by hydropower or wind energy. In other countries a net contribution to the energy supply is achieved only if they have a high performance factor.
- Solar drying of agricultural crops is in many cases a viable technological and economical option. The next step is market introduction.
- Solar cooking provides a significant beneficial impact. Many hundreds of thousands of solar cooking devices have been sold, but they have limitations and can only supplement conventional fuel use.

Hydroelectricity

There is a general view that hydroelectricity is the renewable energy source par excellence, non-exhaustible, non-polluting, and more economically attractive than other options. And although the number of hydropower plants that can be built is finite, only a third of the sites quantified as economically feasible are tapped.

Hydropower plants emit much less greenhouse gas than do thermal plants. Greenhouse gas emissions of hydropower are caused by the decay of vegetation in flooded areas and by the extensive use of cement in the dam construction. Unfortunately, there are local impacts of the use of rivers, social as well as ecological, and they are gaining importance as people become aware of how those impacts affect living standards.

Most renewable sources of energy hydroelectricity generation are capital intensive but have lower operational costs than thermal and nuclear options. The high initial cost is a serious barrier for its growth in developing countries where most of the untapped economic potential is located.

The potential of hydroelectricity

Chapter 5 provides extensive information on the theoretical and technical potential of hydroelectricity. An overview is given in table 7.18, which also presents the economically feasible potential, estimated at 8,100 terawatt-hours a year.

In 1997 total installed hydroelectric capacity was about 660 gigawatts, of which about 23 gigawatts were small scale (plant capacity of less than 10 megawatts). About a fifth of the world electricity supply, hydroelectricity produced 2,600 terawatt-hours (*World Atlas,* 1998), of which about 3.5 percent (about 90 terawatt-hours) was in small hydroelectric plants.

In some regions (North America, Western Europe, Pacific OECD countries) more than 65 percent of the economically feasible potential is already in use. In others (Sub-Saharan Africa, centrally planned Asia, India) less than 18 percent of the potential is in use (see table 7.18). In Latin America and the Caribbean nearly 44 percent of the economically feasible potential is already tapped. Since the OECD operational capacity is at 80 percent of the economic potential, most experts believe this value to be an upper limit for capacity installation.

In 1997 the hydro capacity under installation was 125 gigawatts. Assuming these plants will have the same average capacity factor as the units already in operation (45 percent), this represents another 490 terawatt-hours a year, or 6 percent of the economically feasible potential. This will push the hydroelectricity production in the first years of the 21st century to at least 3,000 terawatt-hours a year. By the middle of this century that could grow to 6,000 terawatt-hours a year (IIASA and WEC, 1998; Johansson and others, 1993a).

In 1997 developing countries had a total installed capacity of 262 gigawatts, soon to grow to about 364 gigawatts (see table 7.18). In 1997 the 70 major developing countries were responsible for 225 gigawatts of installed capacity (*World Atlas,* 1998). In 1989–97 these 70 countries' installed capacity increased by 40 gigawatts, or about 22 percent (2.5 percent a year),[2] much less than the 5.7 percent a year growth forecast by Moore and Smith (1990). The significant slowdown in the construction of hydroelectric plants in developing countries, compared with 1970–90 (Moore and Smith, 1990; Churchill, 1994), can mainly be explained by shortages of capital and difficulties in finding financing abroad.

Hydroelectric technology development

Technologies to reduce dam construction and power generation costs. Hydroelectricity generation is usually regarded as a mature technology, unlikely to advance. That may be so for the efficiency and cost of conventional turbines, where the large number of units constructed has led to an optimised design. But for small-scale hydropower, there is room for further technical development. Examples include the use of variable speed turbines at low heads, induction generators, electronic control and telemetry, submersible turbo-generators, new materials, and the further development of innovative turbines (EUREC Agency, 1996; Schainker, 1997).

Only a third of the sites quantified as economically feasible for hydroelectricity production are tapped.

On dam construction, there has recently been further progress, especially with roller compacted concrete (RCC) dams. The lower cement content and the mechanised placing of the concrete yield a relatively low unit cost of around $30–40 per cubic metre of dam body, less than half the price of conventional placed concrete. Due to the rapid concrete placement with the RCC technique, dams can grow by 60 centimetres a day, making it possible to build a 200-metre high dam in less than a year (Oud and Muir, 1997). With RCC dams, river diversion during construction is often in-river, rather than by diversion tunnels, saving time and money. The RCC technology has made many dams feasible that previously appeared economically unattractive (Oud and Muir, 1997). For smaller structures, dams with geo-membrane lining (up to 80 metres high) and inflatable rubber weirs (up to 15 metres high) are becoming acceptable alternatives to concrete weirs and low rock-fill or earth-fill dams.

Other parts of the operational system, such as spillways, are now better understood, allowing the use of higher specific discharges per meter width of the spillway chute, saving on cost (Oud and Muir, 1997). Tunnel-boring machines are becoming more attractive. Underground water conduits are attractive because they do not disturb the landscape (Oud and Muir, 1997). Power houses and control rooms are being designed to cut costs and manufacturing time of hydroelectric equipment.

The present installed system cost ranges from $1,000–1,500 a kilowatt for the most favourable sites. In practice cost figures of $3,000 a kilowatt and higher are also found. There are some expectations that technology advances can reduce costs, but in small amounts since the present technology is well optimised. With low investment costs and favourable financing conditions (interest 6 percent a year and 30 years for payment), generation costs for an average capacity factor of 45 percent is $0.04–0.06 a kilowatt hour. At higher capacity factors and with longer payback times, lowest generations costs of about $0.02 a kilowatt hour are found. Because the plant is usually placed far from the point of electricity use, investment can also be required for transmission, perhaps adding another $0.01 per kilowatt-hour.

For small-scale hydropower, the unit cost is expected to be higher than for large-scale hydro. But with the choice of very favourable sites, the use of existing administrative structures and existing civil works for flood-control purposes, avoiding the use of cofferdams during installation, and refurbishing of old sites, electricity production costs may come down from $0.04–0.10 a kilowatt-hour to $0.03–0.10 a kilowatt-hour.

Technologies to reduce social and ecological impacts. Considering the criticism of hydropower production, especially when large dams are built, modern construction tries to include in the system design several technologies that minimise the social and ecological impacts. Some of the most important impacts are changes in fish amount and fish biodiversity, sedimentation, biodiversity perturbation, water quality standards, human health deterioration, and downstream impacts (see also chapter 3).

- *Changes in fish amount and fish biodiversity.* Technologies are being pursued to preserve subsistence and commercial fish production as well as fish biodiversity. Further R & D is being recommended to achieve a quantitative understanding of the responses of fish to multiple stresses inside a turbine and to develop biological performance criteria for use in advanced turbine design (National Laboratory, 1997). Inclusion of passage facilities, such as fish ladders (Goodland, 1997), are becoming a necessity for renewing dam operational contracts in the United States. In tropical countries, where such technology is not useful, electric luring of fish into containers or elevators, as carried out in Yacyreta(between Argentina and Paraguay), may be a solution (Goodland, 1997). Because most new dams will be built in tropical countries, it is necessary to carry out extensive studies to identify new or rare species and determine if they can live in adjacent rivers not slated for damming (Goodland, 1997).
- *Sedimentation.* Sedimentation increases strongly when catchments are developed. Another possibility is the sporadic filling of the reservoir with large amount of land due to land slide or due to some exceptional flood (Goodland, 1997). Such problems can be minimised through watershed management, debris dams, sediment bypassing, sediment flushing, sediment sluicing, sediment dredging, and using reservoir density currents.
- *Biodiversity perturbation.* Conservation of biodiversity demands, at the least, no net loss of species. This requires complete knowledge of what is present before the dam is built, which is difficult. The main conservation measures have become site selection and selection of reservoir size. In practice, the conservation of onsite biodiversity depends on not flooding large areas, particularly intact habitats such as tropical forests, and on conserving an offset in perpetuity (Goodland, 1997).
- *Water quality.* Initially water quality is mainly disturbed by the large amount of biomass left in the flooded area and by filling the reservoir. This can be mitigated by removing biomass and by filling the reservoir at a moderate rate. After filling, thermal stratification frequently occurs in reservoirs with a long water residence time (full seasons cycle) and water depths of more than 10 metres. Reservoir stratification can release water of colder or warmer temperatures than the river would experience without a dam, with positive or negative impacts on the river fishery. It can be minimised through (1) changes in inlet structure configuration, (2) in-reservoir de-stratification, (3) multilevel outlet works for mitigation of downstream effects, and (4) positive mixing and aeration by fountain jets or compressed air. But sufficient knowledge is not yet available, and further R&D is recommended (National Laboratory, 1997).
- *Human health deterioration.* Reservoirs can cause epidemics of three water-related diseases: malaria, schistosomiasis, and Japanese B encephalitis. The proliferation of malaria and encephalitis

can be avoided with chemicals and chemotherapy. But resistance of mosquitoes and *Plasmodium* protozoan parasite makes malaria increasingly expensive to control. Schistosomiasis is better controlled by chemotherapy.

- *Downstream impacts.* Downstream social impacts can exceed upstream resettlement upheavals, and they deserve more attention than is common nowadays. Cessation of annual fertile silt and moisture deposition leads to declining yields, grazing impairment, fish and wildlife decline, and erosion at the mouth of the river, due to the reduction in suspended particles that replace the land normally washed out by the ocean. In addition, the decline in water availability and agricultural yields increases the competition for water and other scarce resources. Furthermore, the construction of a dam forces people who are long adapted to cyclical floods to switch suddenly to rainfed livelihoods (Goodland, 1997). Some of these issues can be mitigated through off-takes at various levels to allow for flexibility of the water temperature in accord with downstream needs, and others through measures that reduce reservoir stratification, including local mixing and shorter water residence time.

System aspects

To even out annual seasonal flow, dams are erected and land areas flooded. Since the flows vary from year to year, every attempt to increase the reliability of the water supply increases the flooded area, and that increase is exponential for reliability above 70 percent (Moreira and Poole, 1993). Another alternative to increase system reliability and reduce cost is hydropower complementation, based on the notion that different river basins can be wire connected, letting a higher flow in one basin compensate for low flow in the other. Hydrologic diversity usually involves large geographic distance, but on either side of the equator distances are modest (Moreira and Poole, 1993).

A third alternative is to use hydroelectricity to store intermittent renewable energy. Storage energy, to ensure reliable, high quality service, will provide for increased renewable use and system stabilisation with distributed generation. Areas of importance include pumped hydro (Schainker, 1997). Further research is recommended to examine the benefits and costs of coupling hydropower to renewable energy storage needs (PCAST, 1997).

TABLE 7.18. HYDROELECTRIC THEORETICAL, TECHNICALLY FEASIBLE, AND ECONOMICALLY FEASIBLE POTENTIAL AS WELL AS INSTALLED AND UNDER INSTALLATION CAPACITY IN 1997, BY REGION (TERAWATT-HOURS A YEAR UNLESS OTHERWISE NOTED)

Region	Gross theoretical potential	Technically feasible potential	Economically feasible potential	Installed hydro capacity (gigawatts)	Installed hydro capacity in developing countries (gigawatts)	Production from hydro plants	Hydro capacity under construction (gigawatts)	Hydro capacity under construction in developing countries (gigawatts)
North America	5,817	1,509	912	141.2	0	697	0.9	0
Latin America and Caribbean	7,533	2,868	1,199	114.1	114.1	519	18.3	18.3
Western Europe	3,294	1,822	809	16.3	16.3	48	2.5	2.5
Central and Eastern Europe	195	216	128	9.1	9.1	27	7.7	7.7
Former Soviet Union	3,258	1,235	770	146.6	16.5	498	6.7	3.9
Middle East and North Africa	304	171	128	21.3	0	66	1.2	0.03
Sub-Saharan Africa	3,583	1,992	1,288	65.7	0	225	16.6	0
Centrally planned Asia	6,511	2,159	1,302	64.3	64.3	226	51.7	51.7
South Asia[a]	3,635	948	103	28.5	28.5	105	13.0	13.0
Pacific Asia[a]	5,520	814	142	13.5	13.5	41	4.7	4.7
Pacific OECD	1,134	211	184	34.2	0	129	0.8	0
World total	**40,784**	**13,945**	**6,965**	**654.8**	**262.3**	**2,581**	124.1	**101.8**
World total[b]	**~40,500**	**~14,320**	**~8,100**	**~660**		**~2,600**	**~126**	

a. Several South Asian and other Pacific Asian countries do not release their economically feasible potential. As a result economically feasible potential for these regions are too low, and in one case for South Asia are even lower than the electricity generated. b. These are the values quoted in the source. They differ from the world total in the previous row mainly due the inclusion of estimates for countries for which data are not available.

Source: World Atlas, 1998.

Modern construction of dams tries to include technologies that minimize the social and ecological impacts.

Environmental and social impacts

The average energy density of hydroelectricity generation shows thatt significant amounts of land have been flooded for this purpose (see chapter 5). If new plants will keep the average energy density (optimistic, since the best sites have already been used), some extra 50 million hectares of land will be flooded to make available two-thirds of the economic potential. This figure may not look so high relative to the land required for biomass energy production, but river surroundings are the most densely inhabited areas in rural regions. Several other environmental impacts in the flooded area can be minimised by convenient choosing of sites where it is possible to store large water volumes in a small area, such as canyons.

With a responsibility to preserve the environment, the overall cost of producing hydropower is increasing. As the hydropower industry moves towards an open market, it is a challenge to figure out how it will survive marginal cost pricing. Some operators with high costs could also find themselves in a restructured environment with old and insufficient generating plant. In the United States several dams associated with power production are being decommissioned, mainly because they disturb commercial fishing or impose a significant onus for biodiversity (Koch, 1996).

A well-understood impact is caused by displacing inhabitants from the flooded area, and mitigating it can represent a significant cost for the project. Some estimates put the displacement cost per person at about six times the annual per capita gross national product (Besant-Jones, 1995)—and others as high as $25,000 per family. Displacing 100,000 inhabitants can add $2 billion to the project cost, enough to make it unfeasible. Strong criticism is always to be expected for hydro projects requiring the relocation of a great number of people. Of utmost importance here is building trust between the people affected by resettlement, the developer, and the authorities; people must know and feel that they matter and that they are taken seriously.

Economic and financial aspects

Hydropower plants are more capital intensive than thermal plants. Historically, hydroelectricity in the developing world has been financed predominantly from public or guaranteed funding. The World Bank has financed about 110 hydroelectric power projects in 50 developing countries, ranging from 6.6 megawatts to 2,240 megawatts, with a combined generating capacity of about 35 gigawatts.

Reliable global data on trends in hydro financing are not available. But World Bank data show a market decline in its lending for hydro—from 3.4 percent to 2.5 percent of the approximately $20 billion it lends annually. There is no doubt that environmental pressures on the Bank (and other multilateral agencies) account for some of this decline (Briscoe, 1998).

In the past few years with the emerging privatisation of the electric sector in developing countries, private capital flows have increased dramatically (Briscoe, 1998). Private activity in infrastructure, previously concentrated in East Asia and Latin America, is now expanding in Eastern Europe and Central Asia, South Asia, and Sub-Saharan Africa. Private infrastructure investment can grow much more, since it accounted for only about 15 percent of all infrastructure investment in developing countries in 1996. Even so, the private sector sees substantial risks, some inherent in the degree to which each hydro project (unlike thermal projects) has to be tailored to specific hydrological, geographic, and geological conditions.

In addition, hydropower project costs have tended to exceed estimates substantially. A World Bank review of 80 hydro projects completed in the 1970s and 1980s indicate that three-fourths had final costs in excess of budget. Costs were at least 25 percent higher for half the projects and 50 percent or more for 30 percent of the projects. Costs were less than estimated on 25 percent of projects (Bacon and others, 1996). Major reasons for such cost increases were unexpected geologic conditions, funding delays, and resettlement problems (Churchill, 1997).

It is essential that the hydro industry comes to grips with the poor record of cost estimation and project implementation. This record has caused the financial community to regard hydro project as riskier than in the past, raising the cost of capital and pricing many hydro projects out of the market. Inadequate resource exploration and site investigation is one reason for the cost and schedule overruns. Governments can solve this by initiating careful resource and site investigations at an early stage using public money. They can recover these costs from the project developer as part of an authorisation or tendering procedure.

It is much easier to involve the private sector in smaller projects, of 40–400 megawatts, where hydropower plants are accepted as environmentally benign if they are run-of-the river, incorporate high head, and are on tributaries to the big rivers (Briscoe, 1998). For larger projects there has been, and will be, little private sector financing unless there is substantial involvement of governments and bilateral and multilateral agencies (Briscoe, 1998).

Conclusion

- Hydropower contributes about 20 percent to the electricity supply, about a third of its potential. The supply of hydroelectricity may grow from 2,600 terawatt-hours a year in 1997 (of which about 3.5 percent from small-scale hydropower) to 3,000 terawatt-hours in the first years of the 21st century and to 6,000 terawatt-hours a year in 2050.
- Hydropower is a clean energy source with many technical advantages over thermal and nuclear plants: operating reserves, spinning reserves, load following services, voltage control, and cold start capability. Some of these characteristics help in aggregating intermittent sources of electricity to the existing system.
- The electricity production cost of large hydroelectricity plants is $0.02–0.08 a kilowatt-hour, with new reductions from technology development offset by the need to mitigate social and environmental

effects. For small hydroelectricity plants, the electricity production cost may come down from $0.03–0.10 a kilowatt-hour to $0.04–0.10 a kilowatts-hour in the long term.

- Improvements and efficiency measures are needed in dam structures, turbines, generators, substations, transmission lines, and environmental mitigation technology to sustain hydropower's role as a clean, renewable energy source. Of utmost importance is building trust between the people affected by resettlement, the developer and the authorities—to address the criticisms regarding social and environmental impacts.
- The emerging liberalisation and privatisation in the electric sector in most industrialised countries may reduce investments in new hydropower plants since they are more capital intensive and riskier than thermal plants.

Geothermal energy

Geothermal energy has been used for bathing and washing for thousands of years, but it is only in the 20th century that it has been harnessed on a large scale for space heating, industrial energy use, and electricity production. Prince Piero Ginori Conti initiated electric power generation with geothermal steam at Larderello in Italy in 1904. The first large municipal district heating service started in Iceland in the 1930s.

Geothermal energy has been used commercially for some 70 years, and on the scale of hundreds of megawatts, 40 years, both for electricity generation and direct use. Its use has increased rapidly in the past three decades—at about 9 percent a year in 1975–95 for electricity and at about 6 percent a year for direct use. Geothermal resources have been identified in more than 80 countries, with quantified records of geothermal use in 46.

The potential of geothermal energy

Exploitable geothermal systems occur in several geological environments. High-temperature fields used for conventional power production (with temperatures above 150° C) are largely confined to areas with young volcanism, seismic, and magmatic activity. But low-temperature resources suitable for direct use can be found in most countries. The ground source heat pump has opened a new dimension in using the Earth's heat, as these pumps can be used basically everywhere.

Geothermal use is commonly divided into two categories—electricity production and direct application. In 1997 world-wide use of geothermal energy amounted to about 44 terawatt-hours a year of electricity and 38 terawatt-hours a year for direct use (table 7.19). A new estimate of world geothermal potential shows the useful accessible resource base for electricity production to be some 12,000 terawatt-hours a year (Björnsson and others, 1998). Since only a small fraction of the geothermal potential has been developed, there is ample space for accelerated use of geothermal energy for electricity generation in the near future.

The scope for direct use of geothermal energy is even more plentiful, as the useful accessible resource base is estimated to be 600,000 exajoules, which corresponds to the present direct use of geothermal energy for some 5 million years (Björnsson and others, 1998). With both ample resources and a relatively mature technology at hand, the question of future development of geothermal energy use boils down to economic and political competitiveness with other energy sources on the markets in different countries.

Recent developments

Electricity production. The growth of the total generation capacity in 1990–98 was about 40 percent (table 7.20), with the largest additions in the Philippines (957 megawatts), Indonesia (445 megawatts), Japan (315 megawatts), Italy (224 megawatts), Costa Rica (120 megawatts), Iceland (95 megawatts), the United States (75 megawatts), New Zealand (62 megawatts), and Mexico (43 megawatts). The most

TABLE 7.19. ELECTRICITY GENERATION AND DIRECT USE OF GEOTHERMAL ENERGY, 1997

Region	Electricity generation			Direct use		
	Installed capacity (gigawatts-electric)	Total production		Installed capacity (gigawatts-thermal)	Total production	
		Terawatt-hours (electric)	Percent		Terawatt-hours (thermal)	Percent
European Union	0.75	3.8		1.03	3.7	
Europe, other	0.11	0.5		4.09	16.1	
Total Europe	0.86	4.3	10	5.12	19.8	52
North America	2.85	16.2		1.91	4.0	
Latin America	0.96	6.9				
Total Americas	3.81	23.1	53	1.91	4.0	10
Asia	2.94	13.0	30	3.08	12.2	32
Oceania	0.36	2.9	6	0.26	1.8	5
Africa	0.05	0.4	1	0.07	0.4	1
World total	**8.02**	**43.8**	**100**	**10.44**	**38.2**	**100**

Source: Based on Stefansson and Fridleifsson, 1998.

TABLE 7.20. INSTALLED GEOTHERMAL ELECTRICITY GENERATION CAPACITY (MEGAWATTS OF ELECTRICITY)

Country	1990	1995	1998
Argentina	0.7	0.7	0
Australia	0	0.2	0.4
China	19	29	32
Costa Rica	0	55	120
El Salvador	95	105	105
France (Guadeloupe)	4	4	4
Guatemala	0	0	5
Iceland	45	50	140
Indonesia	145	310	590
Italy	545	632	769
Japan	215	414	530
Kenya	45	45	45
Mexico	700	753	743
New Zealand	283	286	345
Nicaragua	70	70	70
Philippines	891	1,191	1,848
Portugal (Azores)	3	5	11
Russia	11	11	11
Thailand	0.3	0.3	0.3
Turkey	20	20	20
United States	2,775	2,817	2,850
Total	**5,867**	**6,798**	**8,239**

Source: Based on IGA, 1999.

progressive of these countries, the Philippines, with 22 percent of its electricity generated with geothermal steam, plans to add 580 megawatts to its installed capacity in 1999–2008 (Benito, 1998). Other countries generating 10–20 percent of their electricity with geothermal are Costa Rica, El Salvador, Kenya, and Nicaragua.

The participation of private operators in steam field developments through BOT (build, operate, and transfer) and BOO (build, own, and operate) contracts and through JOC (joint operation contracts) have significantly increased the speed of geothermal development in the Philippines (Vasquez and Javellana, 1997) and Indonesia (Radja, 1997; Aryawijaya, 1997). And several developing countries are considering the participation of private operators.

The electricity generation cost is variable—commonly around $0.04 a kilowatt-hour for modern, cost-effective plants, but ranging from $0.02–0.10 a kilowatt-hour. The installed system costs may range from $800–3,000 a kilowatt-hour. With cost reductions and under favourable conditions the cost can come down to $0.01–0.02 a kilowatt-hour.

Direct use of geothermal energy. Direct application of geothermal energy can involve a wide variety of end uses, such as space heating and cooling, industry, greenhouses, fish farming, and health spas. It uses mostly existing technology and straightforward engineering. The technology, reliability, economics, and environmental acceptability of direct use of geothermal energy have been demonstrated throughout the world.

Compared with electricity production from geothermal energy, direct use has several advantages, such as much higher energy efficiency (50–70 percent compared with 5–20 percent for conventional geothermal electric plants). Generally the development time is much shorter, and normally much less capital investment is involved. And possible for high- and low-temperature geothermal resources, direct use is much more widely available in the world. But it is more site specific for the market, with steam and hot water rarely transported long distances from the geothermal site. The longest geothermal hot water pipeline in the world, in Iceland, is 63 kilometres.

The production costs for direct use are highly variable, but commonly under $0.02 a kilowatt-hour. The production costs might range from $0.005–0.05 a kilowatt-hour (thermal energy), and the turnkey investments costs from $200–2,000 a kilowatt.

The two countries with the highest energy production (Japan and Iceland) are not the same as the two with the highest installed capacities (China and the United States), because of the variety in the load factors for the different types of use (table 7.21).

Lund (1996) has recently written a comprehensive summary on the various types of direct use of geothermal energy. Space heating is the dominant application (33 percent). Other common applications are bathing/swimming/balneology (19 percent), greenhouses (14 percent), heat pumps for air conditioning and heating (12 percent), fish farming (11 percent), and industry (10 percent).

Heat pump applications. Geothermal energy previously had considerable economic potential only in areas where thermal water or steam is found concentrated at depths less than 3 kilometres, analogous to oil in commercial oil reservoirs. This has changed recently with developments in the application of ground source heat pumps—using the Earth as a heat source for heating or as a heat sink for cooling, depending on the season. These pumps can be used basically everywhere.

Switzerland, not known for hot springs and geysers, shows the impact geothermal heat pumps can have—generating about 230 gigawatt-hours a year in 1994 (Rybach and Goran, 1995). In the United States, at the end of 1997, more than 300,000 geothermal heat pumps were operating nation-wide in homes, schools, and commercial buildings for space heating and cooling (air conditioning), providing 8–11 terawatt-hours a year of end-use energy according to different estimates.

Geothermal heat pumps are rated among the most energy-efficient space conditioning equipment available in the United States. Reducing the need for new generating capacity, they perform at greater efficiencies than conventional air source heat pumps used for air conditioning. Several electric utilities have introduced financial incentive schemes by encouraging house owners to use groundwater heat pumps for space cooling and heating purposes and thus reducing the peak loads on their electric systems. The Geothermal Heat Pump Consortium has established a $100 million 6-year program to increase the geothermal heat pump unit sales from 40,000 to 400,000 annually, which will reduce greenhouse gas emissions by 1.5 million metric tonnes of carbon equivalent annually (Pratsch, 1996). A third of the funding comes from the U.S. Department of Energy and the Environmental Protection Agency, two-thirds from the electric power industry. Financial incentive schemes have also been set up in Germany and Switzerland.

Potential market developments

Some 80 countries are interested in geothermal energy development, of which almost 50 now have quantifiable geothermal use. A world-wide survey (Fridleifsson and Freeston, 1994) showed that the total investments in geothermal energy in 1973–92 were about $22 billion. In 1973–82 public funding amounted to $4.6 billion, private funding to $3 billion. In 1983–92 public funding amounted to $6.6 billion, private funding to $7.7 billion. Of special interest, private investment in geothermal rose by 160 percent from the first decade to the second, while public investments rose by 43 percent, showing the confidence of private enterprises in this energy source and demonstrating its commercial viability.

Extrapolations of past trends show the long-term prognosis for potential development. In 1975–95 the growth of the installed capacity for electricity generation world-wide was about 9 percent a year. If this rate continues for another 25 years, the installed capacity would be 25 gigawatts of electricity in 2010 and 58 gigawatts of electricity in 2020 (table 7.22). The annual electricity generation shown in table 7.22 is based on the assumption that the use factor will be similar to that in 1997 (Stefansson and Fridleifsson, 1998). In 1990–98 the annual growth was close to 4 percent a year, not 9 percent. So, new incentives are needed to realise this scenario.

The average growth in the direct use of geothermal energy can be estimated at about 6 percent a year in the past decade. With annual growth rate of 6 percent in the near future, the installed capacity would be around 22 gigawatts of thermal energy in 2010 and 40 gigawatts of thermal energy in 2020 (see table 7.22). This is not taking into account the rapid development of ground-based heat pumps in recent years. In a matter of some years, this sector has grown from infancy to 1,400 megawatts of thermal energy in the United States alone. Development is also fast in Switzerland, Germany, and Sweden. The forecast for direct use therefore might be somewhat pessimistic.

The U.S. Department of Energy's Office of Geothermal Technologies recently identified five strategic goals for geothermal energy as a

TABLE 7.21. GEOTHERMAL ENERGY PRODUCTION WITH DIRECT USE IN COUNTRIES WITH MORE THAN 40 MEGAWATTS-THERMAL INSTALLED CAPACITY

Country	Installed capacity (gigawatts-thermal)	Heat production (terawatt-hours a year)
Japan	1.16	7.50
Iceland	1.44	5.88
China	1.91	4.72
United States	1.91	3.97
Hungary	0.75	3.29
Turkey	0.64	2.50
New Zealand	0.26	1.84
France	0.31	1.36
Italy	0.31	1.03
Germany	0.31	0.81
Georgia	0.25	n.a
Serbia	0.09	0.67
Russia	0.21	0.67
Romania	0.14	0.53
Switzerland	0.19	0.42
Slovak Rep.	0.08	0.38
Sweden	0.05	0.35
Tunisia	0.07	0.35
Bulgaria	0.10	0.35
Israel	0.04	0.33
Macedonia FYR	0.08	0.15
Poland	0.04	0.14

Source: Based on Stefansson and Fridleifsson, 1998.

TABLE 7.22. POTENTIAL DEVELOPMENT OF THE INSTALLED CAPACITY AND ENERGY PRODUCTION FROM GEOTHERMAL SOURCES IN THE FORM OF ELECTRICITY AND DIRECT USE OF HEAT, 1997–2020

Year	Gigawatts-electric	Terawatt-hours (electric)	Gigawatts-electric	Terawatt-hours (thermal)
1997	8.0	43.8	10.4	38.20
2010	24	134	22	81
2020	58	318	40	146

Not until the 20th century has geothermal energy been harnessed on a large scale for space heating, industrial energy use, and electricity production.

preferred alternative to polluting energy sources (USDOE OGT, 1998), including:

- Supply the electric power needs of 7 million U.S. homes (18 million people) from geothermal energy by 2010.
- Expand direct uses of geothermal resources and application of geothermal heat pumps to provide the heating, cooling, and hot water needs of 7 million homes by 2010.
- Meet the basic energy needs of 100 million people in developing countries by using U.S. geothermal technology to install at least 10 gigawatts by 2010.

Environmental aspects

Geothermal fluids contain a variable quantity of gas—largely nitrogen and carbon dioxide with some hydrogen sulphide and smaller proportions of ammonia, mercury, radon, and boron. The amounts depend on the geological conditions of different fields. Most of the chemicals are concentrated in the disposal water, routinely re-injected into drill holes, and thus not released into the environment. The concentrations of the gases are usually not harmful, and the removal of such gases as hydrogen sulphide from geothermal steam is a routine matter in geothermal power stations where the gas content is high. The range in carbon dioxide emissions from high-temperature geothermal fields used for electricity production in the world is 13–380 grams a kilowatt-hour, less than for fossil fuel power stations. Sulphur emissions are also significantly less for geothermal than fossil fuel electric power stations.

The gas emissions from low-temperature geothermal resources are normally only a fraction of the emissions from the high-temperature fields used for electricity production. The gas content of low-temperature water is in many cases minute—in Reykjavik, Iceland, the carbon dioxide content is lower than that of the cold groundwater. In sedimentary basins, such as the Paris basin, the gas content may be too high to be released. In such cases the geothermal fluid is kept at pressure within a closed circuit (the geothermal doublet) and re-injected into the reservoir without any degassing. Conventional geothermal schemes in sedimentary basins commonly produce brines that are generally re-injected into the reservoir and thus never released into the environment. The carbon dioxide emission from these is thus zero.

Conclusion

- Geothermal energy has been used commercially for 70 years, both for electricity generation and direct use, with use increasing rapidly in the past three decades. In 1975–95 the growth rate for electricity generation was about 9 percent a year and in recent years about 4 percent a year. For direct use it was about 6 percent a year.
- For the 46 countries with records of geothermal use the electricity generated was 44 terawatt-hours of electricity and the direct use 38 terawatt-hours of thermal energy in 1997, and 45 terawatt-hours of electricity and 40 terawatt-hours of thermal energy in 1998.
- Assuming world-wide annual growth to average 9 percent a year through 2020, the electricity production may reach about 130 terawatt-hours in 2010 and about 310 terawatt-hours in 2020. Assuming the annual growth rate for direct use to continue at 6 percent, the energy production may reach about 80 terawatt-hours in 2010 and about 140 terawatt-hours in 2020.
- Recent developments in the application of the ground source heat pump opens a new dimension in the scope for using the Earth's heat. Heat pumps can be used basically everywhere and are not site-specific, as conventional geothermal resources are.
- Geothermal energy, with its proven technology and abundant resources, can make a significant contribution towards reducing the emission of greenhouse gases. But it requires that governments implement policies and measures to improve the competitiveness of geothermal energy systems with conventional energy systems.

Marine energy technologies

The oceans, covering more than two-thirds of the Earth, represent an enormous energy resource containing vastly more energy than the human race could possibly use. The energy of the seas is stored partly as kinetic energy from the motion of waves and currents and partly as thermal energy from the sun. (Chapter 5 summarises the nature and scale of the ocean energy resource.)

Although most marine energy is too diffuse and too far from where it is needed to be economically exploited, in special situations it can be effectively captured for practical use. Tidal energy needs the more extreme tidal ranges or currents. Wave energy needs to be exploited in places with a higher-than-average wave climate. Ocean thermal energy conversion needs as large a temperature difference as possible between the surface waters and the water near the seabed. Such requirements tend to limit the use of the resource to certain areas of coastline offering the coincidence of a suitably intense resource and a potential market for the energy. This makes many published estimates of enormous global marine energy resources academic.

The potential and technology of marine energy

The main marine energy resources can be summarised, in order of maturity and use, as:

- Tidal barrage energy.
- Wave energy.
- Tidal/marine currents.
- Ocean thermal energy conversion (OTEC).
- Salinity gradient/osmotic energy.
- Marine biomass fuels.

Exploiting salinity gradients and the cultivation of marine biomass are not discussed because their exploitation seems a long way from any practical application, though new research might clarify their potential.

Tidal barrage energy. The rise and fall of the tides creates, in effect, a low-head hydropower system. Tidal energy has been exploited in this way on a small scale for centuries in the form of water mills. The one large modern version is the 240 megawatt-electric La Rance scheme, built in France in the 1960s, the world's largest tidal barrage, using a conventional bulb turbine. A handful of smaller schemes have also been built.

Numerous studies have been completed for potentially promising locations with unusually high tidal ranges, such as the Bay of Fundy in Canada and the 7-gigawatt scheme for the Severn Estuary in the United Kingdom. But most schemes of this kind have proved to be extremely large and costly. The proposed Severn Barrage scheme—which the U.K. government decided not to pursue—would have involved the use of 216 turbo-generators, each nine metres in diameter and 40 megawatts in capacity. The load factor would have been around 23 percent, the cost an estimated $12 billion (Boyle, 1996).

The combination of high costs, major environmental impact, and poor load factors makes this technology generally unattractive, but there may be occasional niche applications for it in the future in especially favourable locations.

Wave energy. Energy can be extracted from waves. As an example, in deep water off the northwest coast of Scotland (one of the more intense wave climates in the world) the average energy along the prevailing wave front can be 70 kilowatts a metre (or more). Closer inshore this falls to an average of around 20 or 30 kilowatts a metre, and along the shoreline to about 10 kilowatts a metre or less. The energy availability is thus sensitive to the distance from the shoreline (ETSU/DTI, 1999).

Wave energy remains at an experimental stage, with only a few prototype systems actually working. All of the few existing systems that have run for more than a few hours are shoreline devices (built into the shore). Total grid-connected wave power is less than 1 megawatt, consisting of several small oscillating water column devices in China, India, and the United Kingdom (YY, 1998). A new generation of larger devices is under development, due to be installed notably in the Azores (Pico) and Japan, as well as in the countries mentioned earlier. The world's wave energy capacity will increase to a few megawatts in the next few years.

If wave energy is to become an important contributor to future energy needs, it will need to move further offshore into deeper water where there are larger and much more energetic waves. This will require a quantum leap in the size and nature of the systems used. Systems capable of surviving under such difficult conditions have not yet been demonstrated, so it is likely to take a decade or more before wave energy can even start to make a contribution to world energy needs (Fraenkel, 1999). Eventually, however, it seems likely to contribute as much as 100 terawatt-hours a year for Europe, and perhaps three times that for the world.

The general immaturity of wave energy technology is illustrated by the variety of solutions proposed for exploiting it. No real consensus has yet emerged as to the 'best' way to convert energy from waves into electricity. Wave energy conversion systems can be classified as:

- Shoreline devices (mounted on the shore).
- Near-shoreline devices (usually installed on the seabed in water less than 20 metres deep).
- Offshore or deep-water devices (usually floating devices moored in deep water with highly energetic wave conditions).

The most popular shoreline device is the oscillating water column (OWC), a large chamber that has a free opening to the sea, encloses an air volume, and is compressed by the wave pressure. A duct between the chamber and the outside atmosphere allows air to be drawn in and out of the chamber as a result of the variation of pressure caused by incoming waves. An air-turbine system, installed in the duct, generates electricity from this reversing air flow.

Most near-shore wave energy converters are designed to be deployed in lines parallel to the shoreline to intercept the wave energy. Another concept is the point absorber, which can occupy a small space yet capture the energy from a larger area surrounding it using resonance effects. Studies show that such arrays can be highly efficient (Randlov and others, 1994). In the longer term other large floating devices, such as the Salter Duck, which relies on modules that rock in response to wave action, will convert the higher power levels available farther offshore.

Tidal and marine current energy. Tidal and marine current energy is the most recent of the marine energy resources to be seriously studied, with most work in the 1990s. The results show that large-scale energy generation from currents requires a totally submerged turbine—and, to be reliable, offshore large, robust systems are required that are only now becoming technically feasible.

In most places the movements of seawater are too slow—and the energy availability is too diffuse—to permit practical energy exploitation. But there are locations where the water velocity is speeded up by a reduction in cross-section of the flow area, such as straits between islands and the mainland, around the ends of headlands, and in estuaries and other such topographical features. As with wind energy, a cube law relates instantaneous power to fluid velocity. So a marine current of 2.5 metres a second (5 knots), not an unusual occurrence at such locations, represents a power flux of about 8 kilowatts a square metre. The minimum velocity for practical purposes is around 1 metre a second (2 knots), about 0.5 kilowatts a square metre. The main siting requirement is thus a location having flows exceeding about 1.5 metres a second for a reasonable period (Fraenkel, 1999; IT Power, 1996).

Data on marine currents are sparse. A major study by the European Commission evaluating the tidal current resource for 106 locations around Europe estimated an exploitable resource from just those sites of 48 terawatt-hours a year (IT Power, 1996). The U.K. government recently came up with an estimate of about 320 megawatts of installed capacity for the United Kingdom by 2010 (ETSU/DTI, 1999). There is potential at known United Kingdom locations to install several gigawatts of tidal turbines. The worldwide potential is obviously much larger.

All that has been done so far is the short-term demonstration of small experimental model systems in the sea, the largest so far being

TABLE 7.23. CURRENT STATUS OF MARINE RENEWABLE ENERGY TECHNOLOGIES

Technology	Maturity	Load factor (percent)	Installed capital cost (dollars per kilowatt)	Unit cost of electricity (dollars per kilowatt-hour)
Tidal barrage	Virtually abandoned	20–30	1,700–2,500	0.08–0.15
Wave–shoreline OWC	Experimental	20–30	2,000–3,000	0.10–0.20
Wave–near shoreline OWC	Commercial 2002–05	25–35	1,500–2,500	0.08–0.15
Wave–offshore – point absorber	Commercial 2010 or later	30–60	2,500–3,000	0.06–0.15
Tidal current turbine	Commercial 2005–10	25–35	2,000–3,000	0.08–0.15
OTEC	Commercial 2005–10	70–80	Unclear	Unclear

only 15 kilowatts, at Loch Linnhe in Scotland in 1994. A Japanese university successfully ran a 3-kilowatt turbine on the seabed off the Japanese coast for some 9 months, and a floating system of about 5 kilowatts was demonstrated in Australian waters. Work is under way to develop and install the first grid-connected tidal current turbine, rated at 300 kilowatts, during 2000.

The various turbine rotor options generally coincide with those used for wind turbines. The two main types are the horizontal axis, axial-flow turbine (with a propeller type of rotor) and the cross-flow or Darrieus turbine, in which blades rotate about an axis perpendicular to the flow. The more promising rotor configuration seems to be the conventional axial flow rotor.

The maximum flow velocity tends to be near the sea's surface, so marine current turbine rotors ideally need to intercept as much of the depth of flow as possible, but especially the near-surface flow. Options for securing a rotor include mounting it beneath a floating pontoon or buoy, suspending it from a tension leg arrangement between an anchor on the seabed and a flotation unit on the surface, and seabed mounting (feasible in shallow water, but more difficult in deeper water). Floating devices have the problem of providing secure anchors and moorings. Seabed-mounted devices seem more straightforward to engineer. One option is a mono-pile set into a socket drilled into the seabed, which seems the most cost-effective solution, just as it is for offshore wind turbines.

Ocean thermal energy conversion. Exploiting natural temperature differences in the sea by using some form of heat engine, potentially the largest source of renewable energy of all, has been considered and discussed for the best part of 100 years (Boyle, 1996). But the laws of thermodynamics demand as large a temperature difference as possible to deliver a technically feasible and reasonably economic system. OTEC requires a temperature difference of about 20 degrees Celsius, and this limits the application of this technology to a few tropical regions with very deep water. Two main processes are used for power production from this source, both based on the Rankine (steam/vapour) cycle:

- The open cycle system flash evaporates warm seawater into vapour (at reduced pressure) and then draws it through a turbine by condensing it in a condenser cooled by cold seawater.
- The closed cycle system uses warm seawater to boil a low-temperature fluid, such as ammonia, which is then drawn through a turbine by being condensed in a heat exchanger with cold seawater and then recycled back to the boiler by a feed pump.

Offshore OTEC is technically difficult because of the need to pipe large volumes of water from the seabed to a floating system, the huge areas of heat exchanger needed, and the difficulty of transmitting power from a device floating in deep water to the shore (SERI, 1989). A few experimental OTEC plants have been tested, notably in Hawaii, but do not seem to offer economic viability. Consequently, OTEC is not likely to make a major contribution to the energy supply in the short to medium term. Shoreline OTEC, however, could be more readily developed and applied economically than devices floating in deep waters.

The latest thinking is that OTEC needs to be applied as a multi-purpose technology: for example, the nutrient-rich cold water drawn from the deep ocean has been found to be valuable for fish-farming. In addition, the cold water can be used directly for cooling applications in the tropics such as air conditioning (NREL, 1999). If OTEC takes off, it is likely to be with energy as a by-product.

Economic aspects

Because of limited experience with the marine renewables, it is difficult to be certain how economic they will be if developed to a mature stage. There is experience (albeit limited) with tidal barrages, but their failure to take off speaks for itself. A rough indication of the relative unit costs of some offshore technologies is given in table 7.23 (Fraenkel, 1999). Several of these options are already competitive in the context of niche markets, such as island communities using conventional small-scale diesel generation, which typically can cost from $0.10 to as much as $0.50 a kilowatt-hour.

Environmental aspects

Offshore environmental impacts for marine energy technologies tend to be minimal. Few produce pollution while in operation. One exception is tidal barrages, where the creation of a large human-made seawater lake behind the barrage has the potential to affect fish and bird breeding and feeding, siltation, and so on. Another exception is OTEC, which may cause the release of carbon dioxide from seawater to the atmosphere.

Wave energy remains at an experimental stage, with only a few prototype systems actually working.

The main issues, however, tend to be conflicts with other users of the seas—for fishing, marine traffic, and leisure activities. Of these, fishing is perhaps the main potential area of conflict. None of the technologies discussed seems likely to cause measurable harm to fish or marine mammals. But some—such as marine current turbines and wave power devices—may need small fishery exclusion zones to avoid entanglement with nets.

Implementation issues

Numerous legal hurdles await developers of offshore technologies in gaining licenses and permissions from the many marine agencies charged by governments with overseeing the environment, navigation, fisheries, and so on. Most of the marine renewable energy technologies are immature and not well developed, facing difficult engineering problems and higher-than-usual financial risks due to the high overheads of running experimental systems at sea. If these technologies are to develop at a reasonable speed to make a significant contribution to clean energy generation, they will need much greater support for RD&D. In the end the power to make marine renewable energy technologies succeed (or fail) lies largely with governments.

Conclusion

- Energy is in the seas in prodigious quantities. The question is whether it can be tapped, converted to a useful form, and delivered cost-effectively in comparison with other methods of energy generation. Several technologies show reasonable prospects for doing so.
- Tidal barrages have been tried in a limited way and abandoned as uneconomic, largely because they are very low-head hydro power plants with unusually high civil costs and an unusually poor load factor.
- Wave energy is beginning to see success with shoreline systems, but has yet to be effectively demonstrated on any scale near shore, let alone offshore, where most of the energy is found.
- Marine current energy is only just starting to be experimented with, but because it involves less technical risk than wave energy (conditions are less extreme), it promises to develop relatively quickly.
- OTEC, experimented with extensively, shows most promise as a multipurpose process (energy with cooling, nutrients for fish-farms, and/or potable water from seawater). Shoreline OTEC may possibly be more readily developed and economically applied than devices floating in deep waters.
- The two remaining known options—exploiting salinity gradients and cultivating marine biomass—seem a long way from any practical application.

System aspects

Rapid changes in the energy sector, liberalisation of energy markets and the success of new technologies such as the combined cycle gas turbine offer challenges to the integration of renewable energy technologies into energy supply systems. They also lead to new issues at the system level.

System aspects come into play when there are many relatively small energy generation units, both renewable and conventional. The issues discussed here focus on electricity because of the instant response of electricity. Few thermal and fuel networks experience these issues because of their storage capacity.

With the rapid increase in the number of small generators connected to distribution networks at low and medium voltages, these networks need to handle more two-way flows of electricity, requiring decentralised intelligent control systems and local storage systems to increase reliability.

Trends in the energy sector

The energy sector is undergoing rapid change because of the following trends:

- World-wide restructuring of utilities and liberalisation of energy markets.
- Greater choice for large and small customers.
- Customer interest in green pricing and the emerging trade in green certificates.
- Technological innovations in efficiency, demand-side management, transport and distribution, electronic power handling, and generation.

These trends directly or indirectly affect the electricity system. Patterson (1999) describes how the global electricity industry is in confusion, how long-accepted ground rules for technology, fuels, ownership, operation, management, and finance are changing by the day. The traditional shape of the electricity system is based on two pillars: large remote power stations generating centrally controller synchronised alternate current, and a monopoly franchise to finance, build, and operate the system.

Technical innovations, such as the gas turbine and advanced power electronics, are undermining the first pillar. Institutional innovation and price competition are undermining the second. In effect liberalisation and new technological development are democratising the system by decentralising it. And suddenly direct current, favoured by Edison, is discussed again, not least because it fits rather better into the micro-applications of computer chips and electronics (FT, 1998).

These trends are also summarised in the concept of the distributed utility, based on the principle that the economies of scale for large generation units are replaced by the economies of numbers in producing large quantities of small units: wind, photovoltaics, fuel cells, internal combustion engines, small gas turbines, and storage systems (Weinberg, 1995; Ianucci and others, 1999). The concept involves both energy efficiency and demand-side management measures at the customers' end, as well as distributed generation and distributed storage in the networks. For the customer it implies, in principle, lower energy prices, new and better services, and new products. Market studies in the United States indicate that in the traditional vertically integrated utility, distributed generation and storage could serve 20–40 percent of U.S. load growth. If the existing load could be served by distributed generation through replacement or retirement of central station generation, the potential is even greater (Ianucci and others, 1999).

Characteristics of renewable energy systems

From a system point of view, a distinction should be made between intermittent renewable energy sources (wind, solar photovoltaic) and those with a more stable and controllable output (hydro, biomass). The intermittent ones deliver primarily energy but only limited capacity, whereas the more stable ones deliver both. Note, however, that an intermittent resource can be transformed to baseload power supply if it is combined with an energy storage system.

Characterising the typical intermittent sources are capacity factors with values often a third or less of those of conventional systems. (The capacity factor is defined as the ratio of year-averaged system power to the rated system power.) In energy output per installed kilowatt, each year conventional power plants produce 4,000–7,000 kilowatt-hours per kilowatt of installed capacity, wind plants generally produce 2,000–2,500, and solar photovoltaic plants produce 750–1,500. The network should be designed to absorb that peak capacity and to provide electricity reliably when the intermittent sources are not available.

The renewable sources with an inherently stable output can, from a system point of view, be treated as conventional units: hydro and biomass-powered units, as well as OTEC and wave power. Hybrid solar thermal power stations co-fired with natural gas (or biofuels) are also regarded as conventional.

Electrical system design

Today's electrical system is designed for one-way traffic from the large generating unit through the transmission and distribution network to the customers. With the advent of smaller generating units distributed throughout the network, two-way traffic becomes more important and requires a rethinking of the network's design. New analytical tools are being developed for this purpose, and innovations in power electronics are becoming more important (Verhoeven, 1999). This is true for transmission lines where high voltage direct current cables (equipped with power electronics at both ends) are preferred for bulk power transport. For medium-and low-voltage lines, power electronics are important in voltage conditioning, preventing voltage dips, and reactive power compensation. The electricity network should become more flexible, facilitating co-operation between generators, storage, and efficient energy consuming systems. In short, the intelligent network of the future will be able to 'talk' to its connected systems (Verhoeven, 1999).

Most studies confirm that an intermittent renewable energy contribution up to 10–20 percent can easily be absorbed in electricity networks.

The effect of decentralised systems on the reliability of the network is of prime concern to the network operators. Studies by KEMA for the Dutch electricity system indicate that by introducing decentralised generators and storage systems (close to the customers) the reliability of the network can increase significantly. Where new grids are to be installed, the grid can become 'thinner' and built with less redundancy. And the transmission and distribution networks can become simpler because of intelligent control systems (Vaessen, 1997).

Model studies by the Pacific Northwest Laboratory confirm that distributed utility (DU) generation will have a significant impact on bulk transmission system stability at heavy penetration levels (Donelly and others, 1996). By locating DU technologies at points of critical loading, utilities may be able to defer upgrades of transmission and distribution facilities. Many utilities have already had operating experience with DU generation, and such local issues such as protection, interaction with distribution automation schemes, and reactive power control have been successfully resolved. Questions remain on how these resources, along with dispatchable generation and storage, interact with each other as their penetration increases.

Grid integration of intermittent renewables

The amount of intermittent power that can be connected to a grid without problems of grid reliability or quality depends on many factors. Locally problems can occur quite soon when feeding substantial intermittent power (more than 100 kilowatts) into the low-voltage grid at one point. But it has been shown that penetration as high as 40 percent can be achieved for wind turbines (feeding into the medium-voltage grid). This is a subject for further investigation. Most studies confirm that an intermittent renewable energy contribution up to 10–20 percent can easily be absorbed in electricity networks. Higher penetration rates may require adequate control or such measures as output limiting or load shedding. Another approach could be to increase the flexibility of the electricity system by means of gas turbines. Penetration values up to 50 percent are possible for large systems with reservoir-based hydropower units (Grubb and Meyer, 1993; Kelly and Weinburg, 1993).

Intermittent renewables and energy storage

Large penetration of intermittent renewable energy technologies would become much easier with some cheap form of large-scale electricity storage, than the virtual storage. At present, however, any other form of electricity storage than the virtual storage offered by conventional plants to the grid seems unattractive.

In the Netherlands several studies in the 1980s analysed the possibilities of large pumped storage systems (storage capacity of 10–30 gigawatt-hours, discharge capacity of 1,500–2,000 megawatts-electric), both above ground and below ground, based on water or compressed air. Estimated investment costs ranged from $1,000 to

$2,000 million (EZ, 1988). The studies were initiated partly because of the (then) estimated limited allowable penetration ratios for wind power into the grid. With the insight that higher penetration ratios were possible, and because of the high investment costs, the immediate interest in storage evaporated.

Schainker provides estimates for the capital costs of electricity storage (Schainker, 1997; PCAST, 1999). Compressed air systems appear to be fairly attractive, both for 2-hour and 20-hour storage options (table 7.24). In Germany the Huntorf power plant near Bremen, commissioned in 1978, used compressed air as a storage medium for the compression part of the gas-turbine cycle. With cheap electricity, the air was stored in off-peak hours, to be used during peak hours as on input to the gas-turbine, co-fired with natural gas.

As noted, wind-generated electricity can be transformed from an intermittent resource to a baseload power supply if combined with compressed air energy storage (CAES), adding probably $0.01 a kilowatt-hour to the wind electricity production costs (Cavallo, 1995).

Value of renewables

For standalone systems, the value of renewables is often the value of the service. Examples are lighting, heating, cooling, cooking, pumping, transportation, and telecommunication. How this value should be evaluated is determined by the minimum cost of any equivalent alternative energy source or technology.

For grid-connected electricity systems, the value of renewables can be defined in different ways: avoided fuel, capacity, and maintenance costs; avoided electricity consumption costs; buy-back rate; and non-financial benefits (Turkenburg, 1992).

The avoided fuel costs in the conventional system usually represent the lowest possible value (typically $0.02–0.05 a kilowatt-hour). Renewables also have a capacity value, though this may be small for intermittent technologies (Alsema and others, 1983; van Wijk and others, 1992). For solar energy systems used for peak shaving (such as peaks due to air conditioning) or grid support, the value of photovoltaic power may be substantially higher than the value of base-load power.

Avoided costs of electricity consumption refer to the situation where a renewable energy system is connected to the grid by a bidirectional kilowatt-hour meter. By definition, the value then becomes equal to the costs (tariffs) of normal electricity. In many countries this is in the range of $0.10–0.25 a kilowatt-hour for small users (IEA PVPS, 1997)

In the buy-back rate method, the value of renewables can be lower or higher than that of energy from the grid. It is lower if an intermediate rate between avoided fuel costs and electricity tariffs is used, as is often the case (IEA PVPS, 1997). It can be higher if a high value is given to the fact that it is green electricity. In some areas (parts of Germany) buy-back rates are based on true costs of renewables and may be as high as about $0.5 a kilowatt-hour for photovoltaics.

Finally, the value of renewables for the owners of a system may partly be non-financial, such as the mere fact that they cover (part of) their own consumption in an independent and clean way. Obviously this cannot be easily expressed in financial terms.

Conclusion

- Current trends in the energy sector favour the emergence of distributed utilities, where growing numbers of relatively small renewable and conventional supply systems can be integrated, thanks to local intelligent control systems supported by local storage systems. When properly planned they can even improve the reliability of the networks, but continued research is required in such areas as network modelling.

TABLE 7.24. OVERVIEW OF CAPITAL COSTS FOR ELECTRICITY STORAGE (1997 DOLLARS)

Technology	Component capital cost		Total capital cost	
	Discharge capacity (dollars per kilowatt)	Storage capacity (dollars per kilowatt-hour)	2-hour storage (dollars per kilowatt)	20-hour storage (dollars per kilowatt)
Compressed air				
Large (350 megawatts)	350	1	350	370
Small (50 megawatts)	450	2	450	490
Above ground (16 megawatts)	500	20	540	900
Conventional pumped hydro	900	10	920	1,100
Battery (target, 10 megawatts)				
Lead acid	120	170	460	3,500
Advanced	120	100	320	2,100
Flywheel (target, 100 megawatts)	150	300	750	6,200
Superconducting magnetic storage (target, 100 megawatts)	120	300	720	6,100
Supercapacitors (target)	120	3,600	7,300	72,000

Source: PCAST, 1999.

> The value of renewables for the owners of a system may partly be non financial, as they cover (part of) their own consumption in an independent and clean way.

- A fundamental change is taking place in the way electricity networks will be managed and used in the near future, thanks to the liberalisation of energy markets and the success of new technologies such as combined-cycle gas turbines and power electronics. The energy sector is moving away from the centralised massive supply of kilowatt-hours into supplying decentralised tailored services to its customers.
- Penetration ratios of renewable energy systems realised without loss of supply security are around 10–20 percent or higher, depending on the characteristics of the total system. High penetration rates can be achieved with advanced power electronics, steadily improving weather prediction methods, availability of hydropower plants, and integration of storage systems.
- The value of energy carriers produced by renewable sources depends on local circumstances. In practice figures are $0.02–1.00 a kilowatt-hour.

Policies and instruments

New renewable energy technologies are trying to make a way into different markets, often in competition with other options to fulfil the demand for energy services. Contrary to assumptions in the 1970s and 1980s, shortages of oil and gas due to resource constraints are not expected in the nearest decades. And coal resources are very large. Increasing fossil fuel prices driven by resource constraints are not also expected in the nearest decades. So a transition to renewables-based energy systems must largely rely on:

- Successful continuing development and diffusion of renewable energy technologies that become increasingly competitive through cost reductions from technological and organisational development.
- Political will to remove various barriers to the deployment of renewables and internalise environmental costs and other externalities that permanently increase fossil fuel prices.

As many countries have demonstrated, a variety of incentive mechanisms can promote the development and use of renewable energy sources:

- The cost of competing conventional energy.
- Financing and fiscal policy.
- Regulation.
- Getting started new technologies.

Cost of competing conventional energy

Reduce subsidies. Subsidies for conventional energy are pervasive and reduce the competitiveness of renewables (chapter 12). They have often proved to be difficult to remove.

Internalise environmental costs. From a theoretical point of view, carbon dioxide taxes would be the simplest and most consistent method for internalising the costs of mitigating climate change. Similarly, taxes can be used to internalise other environmental costs associated with fossil fuels or external costs associated with nuclear power. Although the magnitude of the environmental cost for various energy supply alternatives is debated, they are relatively lower for renewable energy.

Markets in many cases adapt quite rapidly to substantial changes in relative prices. Swedish carbon taxes are a case in point. The new energy and carbon taxes introduced in the early 1990s made bio-energy the least expensive fuel for heat production. Boilers are relatively flexible regarding fuel choice, and the market share of bio-energy in district heat production in Sweden increased from 9 percent (3.6 terawatt-hours) in 1990 to 30 percent (13.7 terawatt-hours) in 1998.

In general, however, this approach has not been particularly successful. Politically, it is difficult to gain acceptance for the large rise in energy prices that this approach could entail. At the national policy level, an important objection is the negative effect on the competitive position of domestic industries. A system of tradable emission permits or high taxes on marginal carbon dioxide emissions might circumvent this problem.

Financing and fiscal policy

Subsidies. Subsidies to stimulate the market penetration of renewables may be seen as the second-best solution to taxes—that is, relative prices are manipulated by subsidising what is desirable rather than taxing what is undesirable. Subsidies can take different shapes: investment subsidies (which give little incentive to actually produce), production subsidies (which may be perceived as unreliable and subject to change), and various indirect subsidies through preferential tax treatment, depreciation rules, and the like (see below). System benefit charges, such as the fossil fuel levy, are increasingly popular mechanisms to finance a subsidy for renewable energy through shifting the economic burden from taxpayers to consumers.

Financing. Financing arrangements are particularly important to renewable energy projects, which are often capital intensive, with many factors making their financing more expensive than for more traditional power investment (Wiser and Pickle, 1997). These factors include real and perceived project risks, the small size of renewable energy industry and many renewable energy projects, and dependence on unpredictable government policies to promote renewable energy.

The right choice of financing schemes (private, corporate, participation, project, and third party), ownership (single, corporate, participation, project finance, and third party) and legal entities (personal, partnership, corporation, and co-operation) can have a decisive impact on the economic viability of a project (Langniss, 1999). In developing countries, financing adapted to local needs and tradition—such as through revolving funds—has proven important in the diffusion of small renewable energy technologies, such as household photovoltaic systems (Gregory and others, 1997). Coping with the demand put on financing by the specific characteristics of renewables is an important challenge for international and other financial institutions.

Taxation. As noted, general and specific tax rules can work for or against renewable energy. Preferential tax treatment, tax exemption, accelerated depreciation, and other approaches can promote renewable energy. The Netherlands, for example, is moving away from using direct subsidies to supporting renewables through a variety of tax incentives. As for other policies and measures, tax mechanisms must be carefully designed to avoid undesirable consequences such as low incentives for project performance, as in the California wind rush, which also disrupted the Danish wind industry when tax incentives where removed (Wiser and Pickle, 1997). Experiences were similar in the initial years of wind power development in India (Mathews, 1998a, b).

Market approaches. Increasing consumer willingness to pay a premium for renewable energy can generate the higher revenues that may be needed to recover production costs. This approach is spreading fast through the increased marketing of environmental labelling and green pricing, notably in North America and Europe. Retail competition and the subsequent need for suppliers to diversify and become more customer oriented is an important driving force, an outcome of the commercial impulse to diversify and add value to basic products. Labelling can be done by a credible independent third party, such as an non-governmental organisation or government agency. In some cases electricity suppliers offer production-specified electricity, such as guaranteed annual average deliveries of wind electricity. The willingness to pay of large electricity users is likely to be low or nil, and green pricing may result only in modest additions of renewable energy. It can, however, nurse a market for new renewable technologies.

Regulation

The focus of most regulatory approaches to promote renewables has been the electricity sector. Regulation has also been used to introduce alternative transportation fuels, notably blending in ethanol with gasoline. Mechanisms to promote renewables through regulatory approaches can be categorised as obligations to buy and obligations to supply. Regulation in other domains can also have an influence.

Obligations to buy. Obligations to buy generally stipulate under what rules independent power producers get access to the grid and economic compensation for delivered electricity. This approach is commonly used in monopoly markets to ensure access for independent power producers with renewable energy. Regulated access and prices reduce transaction costs. Prices are usually based on avoided costs to the utility, and the principles by which these are calculated are important for the outcome. Obligations to buy may be complicated to maintain in liberalised electricity markets with competition between suppliers. The obligation to buy under the U.K. Non Fossil Fuel Obligation has been complemented with a mechanism for reimbursing electricity companies for the extra cost incurred.

Obligations to supply. Renewable portfolio standards can be used as an alternative to, or in combination with, system benefit charges to promote renewable electricity. A renewable portfolio standard imposes an obligation on all electricity suppliers to include a stipulated fraction of renewable electricity in their supply mix. This obligation is sometimes combined with a system for renewable energy credits to facilitate trade of renewable electricity between suppliers. Renewable portfolio standards are being implemented or discussed in Europe and in several states in the United States. Voluntary or negotiated agreements are sometimes used as an alternative to regulation.

Regulation in other domains. Regulation and policies in other sectors or domains (agricultural policy, land-use planning), or the lack thereof, often inflict serious constraints or barriers to the use of renewable energy. For bio-energy, the prospects generally depend heavily on forestry and agricultural policy. In temperate regions a prime option for bio-energy is short rotation forests on agricultural land. But establishing an energy plantation means committing the land to one use for many years or even decades. In contrast, agricultural subsidies tend to change frequently, deterring most farmers from making this commitment.

A lack of regulation can also hinder exploitation. For example, the exploration and exploitation of such natural resources as minerals or fossil fuels are usually regulated through legislation and involve selling or giving concessions. The absence of corresponding regulation for wind concessions, which would secure the rights to a resource, can be a barrier to commercial investments in exploration and exploitation (Brennand, 1996). Consequently, coherence should be sought between regulation in the renewable energy area and in other domains.

Getting new technologies started

Widespread diffusion of new renewable energy technology also depends on a successful chain of research, development, deployment, and cost reduction before a technology is commercially viable. Once that stage is reached, success also depends on availability of information about the resources, technologies, and institutional, organisational, and technical capabilities to adopt a technology to local conditions. This complex process, called the energy technology innovation pipeline, includes research, development, demonstration, buying down the cost of innovative energy technologies along their learning curves, widespread deployment, and involving of a range of actors (PCAST, 1999).

Research and development spending and priorities. In many areas, including the energy sector, the private sector under-invests in RR&D relative to the public benefits that could be realised from such investments, motivating public support for energy R&D. There are several examples of how electricity and gas sector restructuring is resulting in cutbacks on energy R&D and a shift to projects with short-term commercial benefits (PCAST, 1999). Government spending on energy R&D is collected and reported by the International Energy Agency for OECD countries (IEA, 1998). Between 1986 and 1996 the total reported annual energy R&D spending decreased by 19 percent, from about \$11.0 billion to about \$9.0 billion (1996 prices). But in the same period spending on energy conservation R&D increased by 64 percent to about \$1.0 billion (1996 dollars) while spending on renewables R&D increased marginally from $700 million in 1986 to $720 million in 1996.

Increasing consumers' willingness to pay a premium for renewable energy can generate the higher revenues that may be needed to recover production costs.

Demonstration and cost-reduction strategies. Demonstrations are necessary to test new energy-technology manufacturing (such as solar photovoltaics or fuel cells) and energy conversion facilities (such as integrated biomass gasification combined cycle plant)—and to prove their technical and economic viability. The private sector may find it difficult to build demonstration plants for various reasons—high capital requirements, required rates of return, high risk, and difficulties to appropriate the long-term benefits. Thus, public support is needed when clear public benefits can be associated with the technology.

In recent years, more attention has been going to the phase between demonstrations and commercial competitiveness. For essentially all technologies and production processes, a substantial amount of experience or learning results from their application, which in turn reduces costs. For various products and processes a 0–30 percent reduction in costs has been observed with each doubling of cumulative production (Neij, 1999). This phenomenon—called the experience curve or learning curve—has motivated private firms to use forward pricing. That is, they initially sell products below production cost under the expectation that learning effects will drive down costs and that profits will be generated later. But for renewable energy, it may be difficult for an individual firm to recover the costs of forward pricing. Here public financial support in combination with other measures can be key to success. In the wind industry in Denmark, a combination of subsidies, physical planning, wind turbine certification, and the like has produced in a thriving industry with a 50 percent share of the world market (see chapter 12).

Building capacity for widespread deployment. Although a technology may be competitive, its widespread deployment also depends on a range of other factors. A new technology may face a range of barriers to its widespread application. These include high perceived risk, high transaction and information costs, uncertainty about resource availability, and low technical and institutional capabilities to handle this new

TABLE 7.25. CURRENT STATUS OF RENEWABLE ENERGY TECHNOLOGIES

Technology	Increase in installed capacity in past five years (percent a year)	Operating capacity, end 1998	Capacity factor (percent)	Energy production 1998	Turnkey investment costs (U.S. dollars per kilowatt)	Current energy cost of new systems	Potential future energy cost
Biomass energy							
Electricity	≈ 3	40 GWe	25–80	160 TWh (e)	900– 3,000	5–15 ¢/kWh	4–10 ¢/kWh
Heat[a]	≈ 3	> 200 GWth	25–80	> 700 TWh (th)	250– 750	1–5 ¢/kWh	1–5 ¢/kWh
Ethanol	≈ 3	18 bln litres		420 PJ		8–25 $/GJ	6–10 $/GJ
Wind electricity	≈ 30	10 GWe	20–30	18 TWh (e)	1,100– 1,700	5–13 ¢/kWh	3–10 ¢/kWh
Solar photovoltaic electricity	≈ 30	500 MWe	8–20	0.5 TWh (e)	5,000–10,000	25–125 ¢/kWh	5 or 6–25 ¢/kWh
Solar thermal electricity	≈ 5	400 MWe	20–35	1 TWh (e)	3,000– 4,000	12–18 ¢/kWh	4–10 ¢/kWh
Low-temperature solar heat	≈ 8	18 GWth (30 mln m^2)	8–20	14 TWh (th)	500– 1,700	3–20 ¢/kWh	2 or 3–10 ¢/kWh
Hydroelectricity							
Large	≈ 2	640 GWe	35–60	2,510 TWh (e)	1,000– 3,500	2-8 ¢/kWh	2-8 ¢/kWh
Small	≈ 3	23 GWe	20–70	90 TWh (e)	1,200– 3,000	4–10 ¢/kWh	3–10 ¢/kWh
Geothermal energy							
Electricity	≈ 4	8 GWe	45–90	46 TWh (e)	800– 3,000	2–10 ¢/kWh	1 or 2–8 ¢/kWh
Heat	≈ 6	11 GWth	20–70	40 TWh (th)	200– 2,000	0.5–5 ¢/kWh	0.5–5 ¢/kWh
Marine energy							
Tidal	0	300 MWe	20–30	0.6 TWh (e)	1,700– 2,500	8–15 ¢/kWh	8–15 ¢/kWh
Wave	—	exp. phase	20–35	—	1,500– 3,000	8–20 ¢/kWh	—
Current	—	exp. phase	25–35	—	2,000– 3,000	8–15 ¢/kWh	5–7 ¢/kWh
OTEC	—	exp. phase	70–80	—	—	—	—

a. Heat embodied in steam (or hot water in district heating), often produced by combined heat and power systems using forest residues, black liquor, or bagasse.

technology. Taxes, financing, fiscal policy, legislation, and regulation are important to address such barriers and have been discussed above.

Information and transaction costs can be the target of specific government initiatives. For example, responsibility for mapping natural resources should lie with the government. Transaction costs can be reduced by simplified permitting procedures, physical planning, use of standardised contracts, and clear regulation for suppliers of electricity and fuels from renewables. Information costs for new technologies and risk may be effectively reduced through a government testing and certification procedure. Governments, as key sponsors of the educational system in most countries, also have an obligation and an opportunity to support education and continuing education for practitioners.

Conclusion

Renewable energy sources supply 56 ± 10 exajoules a year (12–16 percent) of total world energy consumption (400 ± 10 exajoules in 1998). The supply is dominated by traditional biomass (probably 38 ± 10 exajoules a year), mostly firewood used for cooking and heating, especially in developing countries in Africa, Asia, and Latin America. A major contribution is made by large hydropower (about 9 exajoules a year). Another major contribution, estimated at 7 exajoules a year, comes from primary biomass used in modern energy conversion processes. The contribution from all other renewables (small hydropower, geothermal, wind, solar, and marine energy) is about 2 exajoules a year.

Of the total biomass energy supply, 16 ± 6 exajoules a year is estimated to be commercial. The total primary energy supply from renewable sources in 1998 used commercially can be estimated at 27 ± 6 exajoules. It is estimated that in 1998 new renewable energy sources—modern bio-energy, small hydropower, geothermal energy, wind energy, solar energy and marine energy—supplied 9 exajoules (about 2 percent).

The enormous potential of renewable energy sources can meet many times the world energy demand. They can enhance diversity in energy supply markets, contribute to long-term sustainable energy supplies, and reduce local and global atmospheric emissions. They can also provide commercially attractive options to meet specific needs for energy services, particularly in developing countries and rural areas, create new employment opportunities, and offer opportunities to manufacture much of the equipment locally (IEA, 1997). A brief overview of the many technologies to exploit them is presented in table 7.25.

A number of factors will have to be overcome to increase the market deployment of renewable energy technologies (IEA, 1997). Many technologies are still at an early stage of development. Their technological maturity will demand continuing research, development, and demonstration. Few renewable energy technologies can compete with conventional fuels on a strict cost basis, except in some niche markets in industrialised countries and in non-grid applications in developing countries. Clearly, the cost of production has to come down. As this chapter shows, substantial cost reductions can be achieved for most technologies, closing gaps and making renewables increasingly competitive (see table 7.25). This requires further technology development and market deployments and an increase in production capacities to mass-production levels.

Scenario studies investigating the potential contribution of renewables to global energy supplies indicate that this contribution might range from nearly 20 percent to more than 50 percent in the second half of the 21st century. We conclude that it is unclear what role renewables will play. Much will depend on the development of fossil-fuel energy supplies and the regulatory environment, especially for greenhouse gases (Eliasson, 1998). Contrary to assmp- tions in the 1970s and 1980s, shortages of oil and gas due to resource constraints are not expected in the nearest decades, and coal resources are very large. Therefore, apart from production and distribution constraints, substantially increasing fossil fuel prices driven by resource constraints are not expected in the nearest decades. In addition, advanced technology developments might allow fossil fuel use with greatly reduced atmospheric emissions (see chapter 8).

A transition to renewables-based energy systems would have to rely largely on successful development and diffusion of renewable energy technologies that become increasingly competitive through cost reductions resulting from technological and organisational development—and on the political will to internalise environmental costs and other externalities that permanently increase fossil fuel prices. Different technologies vary widely in their technological maturity, commercial status, integration aspects, and so on. Policies aimed at accelerating renewable energy must be sensitive to these differences. As renewable energy activities grow and ever more extensive funding is required, many countries are moving away from methods that let taxpayers carry the burden of promoting renewables, towards economic and regulatory methods that let energy consumers carry the burden. ■

Notes

1. The capacity of a photovoltaic cell, module, or system is defined as the generating capacity at an irradiance of 1,000 watts a square metre (spectrum AM 1.5) and a cell temperature of 25 degrees Celsius.

2. This figure is obtained by comparing the 1989 installed potential of the 70 developing countries (185 gigawatts) from Moore and Smith (1990) and the value for 1997 (225 gigawatts) obtained from table 7.18.

References

Alsema, E.A., A.J.M. van Wijk, and W.C. Turkenburg. 1983. "The Capacity Credit of Grid-Connected Photovoltaic Systems." In *Proceedings of the 5th EC PV Solar Energy Conference.* Reidel, Dordrecht, Netherlands.

Alsema, E.A., and E. Nieuwlaar, eds. 1998. "Environmental Aspects of PV Power Systems": *Progress in Photovoltaics—Research and Applications.* Vol. 6, no 2.

Alsema, E.A., P. Frankl, and K. Kato. 1998. "Energy Pay-back Time of Photovoltaic Energy Systems: Present Status and Prospects." In J. Schmid and others, eds., *Proceedings of the Second World Conference and Exhibition on PV Solar Energy Conversion.* Report EUR 18656 EN. Brussels.

Andersson, B.A. 1998. "Materials, Availability, and Waste Streams for Large Scale PV." In *Proceedings of the BNL/NREL Workshop on PV and the Environment.* Keystone, Colo.

Aryawijaya, R. 1997. "Government Regulations on Geothermal Development and Environmental Protection in Indonesia." In *Proceedings of the NEDO International Geothermal Symposium.* Sendai, Japan.

Bacon, R.W., J.E. Besant-Jones, and J. Heidarian. 1996. *Estimating Construction Costs and Schedules—Experience with Power Generation Projects in Developing Countries.* World Bank Technical Paper 325, Energy Series. Washington, D.C.

Benito, F.A. 1998. "The Role of Government in Philippine Geothermal Energy Development." Paper presented at the 20th Anniversary Geothermal Workshop of the United Nations University Geothermal Training Programme, Reykjavik, Iceland.

Besant-Jones, J. 1995. "Attracting Finance for Hydroelectric Power." Finance, Private Sector, and Development Energy Note 3. World Bank, Washington, D.C.

Beurskens, H.J.M. 2000. "Offshore Wind Turbine Systems in Europe." Paper presented to the Workshop Technische Machbarkeit der Windenergienutzung im Offshore der Nordsee, Kiel, Germany.

Beyea, J., J. Cook, D. Hall, R. Socolow, and R. Williams. 1991. *Towards Ecological Guidelines for Large-scale Biomass Energy Development: Executive Summary.* National Aubudon Society, Princeton University, N.J.

Björnsson, J., I.B. Fridleifsson, T. Helgason, H. Jonatansson, J.M. Mariusson, G. Palmason, V. Stefansson, and L. Thorsteinsson. 1998. "The Potential Role of Geothermal Energy and Hydro Power in the World Energy Scenario in Year 2020." In *Proceedings of the 17th WEC Congress.* Houston, Tex.

Böer, K.W., ed. 1998. *Advances in Solar Energy.* Vol. 12. Boulder, Colo.: American Solar Energy Society.

Bohland, J., T. Dapkus, K. Kamm, and K. Smigielski. 1998. "Photovoltaics as Hazardous Materials; the Recycling Solution." In J. Schmid, and others, eds., *Proceedings of the Second World Conference and Exhibition on PV Solar Energy Conversion.* Report EUR 18656 EN. Brussels.

Borjesson, P. 1999. "Environmental Effects of Energy Crop cultivation in Sweden—I: Identification and Quantification, and II: Economic Evaluation." *Biomass and Bioenergy* 16 (2): 137–70.

Bouma, J. 1999. "Heat Pump Market in Europe." In *Proceedings 6th IEA Heat Pump Conference.* Berlin.

Boyle, G., ed. 1996. *Renewable Energy: Power for a Sustainable Future.* Oxford: Oxford University Press.

Brennand, T. 1996. "Concessions for Wind Farms: A New Approach to Wind Energy Development." Report prepared for Council for International Co-operation on Environment and Development, Working Group on Energy Strategies and Technologies, Beijing.

Bridgewater, A.V. 1998. "The Status of Fast Pyrolysis of Biomass in Europe." In *Proceedings of the 10th European Biomass Conference and Technology Exhibition*. Wurzburg, Germany.

Briscoe, J. 1998. "The Financing of Hydropower, Irrigation and Water Supply Infrastructure in Developing Countries." Paper prepared for the United Nations Commission on Sustainable Development, New York.

Brouwer, L.C., and L. Bosselaar. 1999. "Policy for Stimulating Passive Solar Energy in the Netherlands." In *Proceedings of the Northsun 1999 Conference.* Edmonton, Canada.

Brown, L.R., J. Abramovitz, C. Bright, C. Flavin, G. Gardner, H. Kane, A. Platt, S. Postel, D. Roodman, A. Sachs, and L. Starke. 1996. *State of the World: A World Watch Institute Report on Progress toward a Sustainable Society.* New York: World Watch Institute.

Bruton, T.M., and others. 1997. "A Study of the Manufacture at 500 MWp p.a. of Crystalline Silicon Photovoltaic Modules. In *Proceedings of the 14th European PV Solar Energy Conference.* Bedford, United Kingdom: H.S. Stephens & Ass.

BTM Consult. 1999: *International Wind Energy Development: World Market Update 1998.* Denmark.

———. 2000. Personal communication. 15 February. Denmark.

Buck, R., E. Lupert, and F. Teelez. 2000. *Proceedings of the 10th SolarPACES International Symposium of Solar Thermal Concentrating Technologies, Solar Thermal 2000.* March 8–10, Sydney.

Burbidge, D., D. Mills, and G. Morrison. 2000. "Stanwell Solar Thermal Power Project." In *Proceedings of the 10th SolarPACES International Symposium of Solar Thermal Concentrating Technologies, Solar Thermal 2000.* March 8–10, Sydney.

Carlson, D.E., and S. Wagner. 1993. "Amorphous Silicon Photovoltaic Systems." In T.B. Johansson, H. Kelly, A.K.N. Reddy, R.H. Wiliams, and L. Burnham, *Renewable Energy: Sources for Fuels and Electricity.* Washington, D.C.: Island Press.

Carpentieri, E., E. Larson, and J. Woods. 1993. "Future Biomass-based Power Generation in North-East Brazil." *Biomass and Bioenergy* 4 (3): 149–73.

Cavallo, A.J. 1995. "High-Capacity Factor Wind Energy Systems." *Journal of Solar Energy Engineering* 117: 137–43.

Churchill, A. A. 1994. "Meeting Hydro's Financing and Development Challenges." *Hydro Review World Wide* 2 (3): 22.

Churchill, A. A. 1997. "Meeting Hydro's Financing and Development Challenges." In T. Dorcey, ed., *Proceedings of the Workshop Large Dams: Learning from the Past, Looking at the Future.* IUCN, World Conservation Union, and World Bank Group; Gland, Switzerland; Cambridge, United Kingdom; and Washington, D.C.

Consonni, S. and E.D. Larson. 1994a. "Biomass-gasifier/Aeroderivative Gas Turbine Combined Cycles, Part A: Technologies and Performance Modelling." Part B: Performance calculations and economic assessment." Paper prepared for the Eighth Congress and Exposition on Gas Turbines in Cogeneration and Utility, Industrial, and Independent Power Generation, October 25–27, Portland, Or.

———. 1994b. "Biomass-gasifer/Aeroderivative Gas Turbine Combined Cycles. Part B: Performance Calculations and Economic Assessment". Paper prepared for the Eighth Congress and Exposition on Gas Turbines in Cogeneration and Utility, Industrial, and Independent Power Generation, October 25–27, Portland, Or.

Dannemand Andersen, P. 1998. *Wind Power in Denmark: Technology, Policies and Results.* Roskilde, Denmark: Riso National Laboratory.

Davis, E. 1995. "Device Developed for Bird Protection." *EPRI Journal* March/April.

Donelly, M.K., J.E. Dagle, and D.J. Trudnowski. 1996. "Impacts of Distributed Utility on Transmission System Stability." *IEEE Transactions on Power Systems* 11 (2): 741–46.

Dyson, T. 1996. "Population and Food, Global Trends and Future Prospects." Global Environmental Change Programme, New York.

EC (European Commission). 1997. "Community Strategy and Action Plan for Renewable Energy Sources." White Paper, Brussels.

———. 1999. "Electricity from Renewable Energy Sources and the International Electricity Market." Working Paper, Brussels.

ECN (Energieonderzoek Centrum Nederland) 1999a. Data Collected for the Shell/Novem/ECN Solar Panel. Personal communication with C.J.J. Tool, Netherlands Energy Research Foundation, Petten, Netherlands.

———. 1999b. *The Role of Renewable Energy in the Netherlands until 2020* (in Dutch). Netherlands Energy Research Foundation, Petten, Netherlands.

Eliasson, B. 1998. *Renewable Energy: Status and Prospects.* Växjö, Sweden: ABB Environmental Affairs.

Elliott, P., and R. Booth. 1993. *Brazilian Biomass Power Demonstration Project.* London: Shell International.

Enermodal. 1999. "Cost Reduction Study for Solar Thermal Power Plants." Paper prepared for World Bank. Enermodal Engineering, Ontario. [www.eren.doe.gov/sunlab/Frame4.htm].

EPIA and Altener. 1996. *Photovoltaics in 2010.* Brussels: Office for Official Publications of the European Commission.

ESIF (European Solar Industry Federation) 1996. *Sun in Action.* Brussels: European Commission.

ETSU (Eldergy Technology Support Unit) and DTI (Department of Trade and Industry) 1999. *New and Renewable Energy: Prospects in the UK for the 21st Century—Supporting Analysis.* Harwell.

EUREC Agency. 1996. *The Future for Renewable Energy: Prospects and Directions.* London: James & James.

EZ (Ministerie van Economische Zaken) 1988. *Storage of Electricity in the Netherlands: Feasible and Acceptable?* (in Dutch). The Hague: Netherlands Ministry of Economic Affairs.

Faaij, A., B. Meuleman, and R. van Ree. 1998. "Long-Term Perspectives of BIG/CC Technology, Performance and Costs." Utrecht University, Deptartment of Science, Technology and Society, and Netherlands Energy Research Foundation, Petten, Netherlands.

Faaij, A., B. Meuleman, W. Turkenburg, A. van Wijk, A. Bauen, F. Rosillo-Calle, and D. Hall. 1998. "Externalities of Biomass Based Electricity Production Compared to Power Generation from Coal in the Netherlands." *Biomass and Bioenergy* 14 (2): 125–47.

Faaij, A., C. Hamelinck, and A.E. Agterberg. Forthcoming. *Long-term Perspectives for Production of Fuels from Biomass: Integrated Assessment and RD&D Priorities.*

Faaij, A., C. Hamelinck, E. Larson, and T. Kreutz. 1999. "Production of Methanol and Hydrogen from Biomass via Advanced Conversion Concepts." In R.P. Overend and E. Chornet, eds., *Proceedings of the 4th Biomass Conference of the Americas.* Oxford: Elsevier Science.

Faaij, A., M. Hekkert, E. Worrell, and A. van Wijk. 1998. "Optimization of the Final Waste Treatment System in the Netherlands." *Resources, Conservation and Recycling* 22: 47–82.

Faaij, A., R. van Ree, L. Waldheim, E. Olsson, A. Oudhuis, A. van Wijk, C. Daey Ouwens, and W. Turkenburg. 1997. "Gasification of Biomass Wastes and Residues for Electricity Production." *Biomass and Bioenergy* 12 (6): 387–407.

Fisch, M.N. 1998. "A Review of Large-Scale Solar Heating Systems in Europe." *Solar Energy* 63 (6): 355–66.

Fraenkel, P.L. 1999. "New Developments in Tidal and Wavepower Technologies." In *Proceedings of the Silver Jubilee Conference: Towards a Renewable Future.* Conference C73 of the Solar Energy Society, May 13–15, Brighton, U.K.

Fridleifsson, I.B., and Freeston, D. 1994. "Geothermal Energy Research and Development." *Geothermics* 23: 175–214.

FT (Financial Times). 1998. "Transforming Electricity."*Financial Times Energy World.* 11: 4–8.

Gardner, G. 1996. "Shrinking Fields: Cropland Loss in a World of Eight Billion." World Watch Paper 131. New York.

Garg, S. 2000. "Manthania Integrated Combined Cycle Project (status note on the 140MW first ISCC project)." In *Proceedings of the 10th SolarPACES International Symposium of Solar Thermal Concentrating Technologies, Solar Thermal 2000.* March 8–10, Sydney.

Garozzo, M, and S. Li Causi. 1998. "The Italian 10,000 Rooftops Program." In J. Schmid and others, eds., *Proceedings of the Second World Conference and Exhibition on PV Solar Energy Conversion.* Report EUR 18656 EN. Brussels.

Glaser, P.E., and others. 1997. *Solar Power Satellites: A Space Energy System for Earth.* Chichester, UK: John Wiley and Sons.

Goodland, R. 1997. "Environmental Sustainability in the Hydro Industry: Disaggregating the Debate." In T. Dorcey, ed., *Proceedings of the Workshop on 'Large Dams: Learning from the Past, Looking in the Future.'* IUCN, World Conservation Union, and World Bank Group; Gland, Switzerland; Cambridge, United Kingdom; and Washington, D.C.

Graham, R. E. Lichtenberg, V. Roningen, H. Shapouri, and M. Walsh. 1995. "The Economics of Biomass Production in the United States." In *Proceedings of the Second Biomass Conference of the Americas.* Portland, Or.

Green, M.A., K. Emery, K. Bücher, D.L. King, and S. Igaru. 1999. "Solar Cell Efficiency Tables (Version 13)." *Progress in Photovoltaics: Research and Applications* 7: 31–37.

Greenpeace and SEI (Stockholm Environment Institute). 1993. *Towards a Fossil Free Energy Future.* Boston: SEI.

Gregory, J., S. Silveira, A. Derrick, P. Cowley, C. Allinson, and O. Paish. *1997 Financing Renewable Energy Projects, a Guide for Development Workers.* London: Intermediate Technology Publications.

Grubb, M.J., and N.I. Meyer. 1993. "Wind Energy: Resources, Systems and Regional Strategies." In T.B. Johansson, H. Kelly, A.K.N. Reddy, R.H. Wiliams, and L. Burnham, *Renewable Energy: Sources for Fuels and Electricity.* Washington, D.C.: Island Press.

Hall, D.O. 1997. "Biomass Energy in Industrialized Countries: A View of the Future." *Forest Ecology and Management* 91: 17–45.

Hall, D.O., F. Rosillo-Calle, R.H. Williams, and J. Woods. 1993. Biomass for Energy: Supply Prospects. In Johansson, T.B, H. Kelly, A.K.N. Reddy, R.H. Wiliams, and L. Burnham, Renewable Energy: Sources for Fuels and Electricity. Washington, D.C.: Island Press.

Hastings, S.R., ed. 1994. *Passive Solar Commercial and Institutional Buildings.* New York: Wiley and sons.

Hemstock, S.L., and D.O. Hall. 1995. "Biomass Energy Flows in Zimbabwe." *Biomass and Bioenergy* 8 (3): 151–73.

Henning, H.M. 1999. "Economic Study of Solar Assisted Cooling Systems." Bericht TOS1-HMH-9905-E01, Fraunhofer Institute ISE, Freiburg, Germany.

Hughes, E.E., and G.A. Wiltsee. 1995. "Comparative Evaluation of Fuel Costs from Energy Crops." In *Proceedings of the Second Biomass Conference of the Americas.* Portland, Or.

Ianucci, J., S. Horgan, J. Eyer, and L. Cibulka. 1999. "Distributed Utility Perspectives." White Paper prepared for the International Energy Agency Renewable Energy Working Party, DU Associates, Livermore, Ca.

IEA (International Energy Agency). 1994. *Biofuels.* Energy and Environment Policy Analysis Series, Organisation for Economic Co-operation and Development and IEA, Paris, France.

———. 1995. *World Energy Outlook.* Paris: IEA and Organisation for Economic Co-operation and Development.

———. 1996. *World Energy Outlook.* Paris: IEA and Organisation for Economic Co-operation and Development.

———. 1997. *Key Issues in Developing Renewables.* Paris: IEA and Organisation for Economic Co-operation and Development.

———. 1998. E*nergy Policies of IEA Countries, 1998 Review.* Paris.

———. 1998. *Proceedings of the Conference on Biomass Energy: Data, Analysis and Trends.* March 23–24, Paris.

IEA (International Energy Agency), CADDET Centre for Renewable Energy. 1998. *Opportunities for Large–scale Purchase of Active Solar Systems.* ETSU, Harwell, U.K.

IEA (International Energy Agency), PVPS (Photovoltaic Power Systems). 1997. *Photovoltaic Power Systems in Selected IEA Member Countries.* Paris.

———. 1998. *Trends in PV Power Applications in Selected IEA Countries between 1992 and 1997.* Report IEA PVPS 1–06. Paris.

IEA (International Energy Agency), REWP (Renewable Energy Working Party). 1999. *The Evolving Renewable Energy Market.* Netherlands: Novem, Sittard.

IGA (International Geothermal Association). 1999. [http://www.demon.co.uk/geosci/igahome.html].

IIASA (International Institute for Applied Systems Analysis) and WEC (World Energy Council). 1998. *Global Energy Perspectives.* Cambridge: Cambridge University Press.

Ishitani, H., and T.B. Johansson, eds. 1996. "Energy Supply Mitigation Options." In R.T. Watson and others, eds., *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses.* Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

IT Power Ltd. 1996. "The Exploitation of Tidal Marine Currents." Tecnomare SpA, Report EUR 16683 EN. European Communities, Office for Official Publications, Luxembourg.

Jager, D. de, A. Faaij, and W.P. Troelstra. 1998. *Cost-effectiveness of Transportation Fuels from Biomass.* ECOFYS. Utrecht University, Department of Science, Technology and Society, Innas B.V, Delft.

Johansson, T. B., H. Kelly, A. K. N. Reddy, and R. Williams. 1993a· "Renewable Fuels and Electricity for a Growing World Economy: Defining and Achieving the Potential." In T. B. Johansson, H. Kelly, A.K.N. Reddy, R.H. Wiliams, and L. Burnham, *Renewable Energy: Sources for Fuels and Electricity.* Washington, D.C.: Island Press.

Johansson, T.B, H. Kelly, A.K.N. Reddy, R.H. Wiliams, and L. Burnham, eds. 1993b. *Renewable Energy: Sources for Fuels and Electricity.* Washington, D.C.: Island Press.

Kaltschmitt, M., C. Rosch, and L. Dinkelbach, eds. 1998. "Biomass Gasification in Europe." Stuttgart University, Institute of Energy Economics and the Rational Use of Energy, Stuttgart, Germany.

Kaltschmitt, M., G.A. Reinhardt, and T. Stelzer. 1996. "LCA of Biofuels under Different Environmental Aspects." Stuttgart University, Institut für Energiewirtschaft und Rationelle Energieanwendung, Stuttgart, Germany.

Kassler, P. 1994. "Energy for Development." Shell Selected Paper. Shell International Petroleum Company, London.

Kelly, H., and C. Weinberg. 1993. "Utility Strategies for Using Renewables." In T. B. Johansson, H. Kelly, A.K.N. Reddy, R.H. Wiliams, and L. Burnham, *Renewable Energy: Sources for Fuels and Electricity.* Washington, D.C.: Island Press.

Koch, A., 1996: "Playing the Electricity Market." *International Water Power and Dam Construction Yearbook.* Sutton, Surrey, England: British Press International.

Kolb, G.J. 1998. "Economic Evaluation of Solar-only and Hybrid Power Towers Using Molten-salt Technology." *Solar Energy* 62 (1): 51–61.

Langniss, O., ed. 1999. "Financing Renewable Energy Systems." Report to the European Commission, German Aerospace Center, Stuttgart, Germany.

Larson, E.D., and H. Jin. 1999a. "Biomass Conversion to Fisher-Tropsch Liquids: Preliminary Energy Balances." In R.P. Overend and E. Chornet, eds., *Proceedings of the 4th Biomass Conference of the Americas.* Oxford: Elsevier Science.

———. 1999b. "A Preliminary Assessment of Biomass Conversion to Fischer-Tropsch Cooking Fuels for Rural China." In R.P. Overend and E. Chornet, eds., *Proceedings of the 4th Biomass Conference of the Americas.* Oxford: Elsevier Science.

Larson, E.D., C.I. Marrison, and R.H. Williams. 1995. "Mitigation Potential of Biomass Energy Plantations in Developing Regions." Princeton University, Center for Energy and Environmental Studies, Princeton, N.J.

Larson, E.D., R.H. Williams, and T.B. Johansson. 1999. "Future Demands on Forests as a Source of Energy." Princeton University, Center for Energy and Environmental Studies, Princeton, N.J.; and United Nations Development Programme, New York.

Larson, E.D., S. Consonni, and T. Kreutz. 1998. "Preliminary Economics of Black Liquor Gasifier/Gas Turbine Cogeneration at Pulp and Paper Mills." Paper prepared for the 43rd ASME gas turbine and aeroengine congress, exposition, and users symposium, June 2–5, Stockholm.

Laue, H.J. 1999. "Heat Pumps, Status and Trends in Europe." In *Proceedings 6th IEA Heat Pump Conference.* Berlin.

Lazarus, M.L., L. Greber, J. Hall, C. Bartels, S. Bernow, E. Hansen, P. Raskin, and D. von Hippel. 1993. "Towards a Fossil Free Energy Future, The Next Energy Transitions: A Technical Analysis for Greenpeace International." Stockholm Environmental Institute and Boston Center.

Lefevre T., J. Todoc, and G. Timilsina. 1997. "The Role of Wood Energy in Asia; Wood Energy Today and Tomorrow (WETT)." Regional Studies, FAO-working paper FOPW/97/2. Food and Agriculture Organization of the United Nations, Rome.

Lenzen, M. 1999. "Greenhouse Gas Analysis of Solar-thermal Electricity Generation." *Solar Energy* 65 (6): 353–68..

Lew, D., R.H. Williams, S. Xie, and S. Zhang. 1998. "Large-Scale Baseload Wind Power in China." *Natural Resources Forum* 22 (3): 165–84.

Little, R.G., and M.J. Nowlan. 1997. "Crystalline Silicon Photovoltaics: The Hurdle for Thin Films." *Progress in Photovoltaics: Research and Applications* 5: 309–15.

Luchi, M. 1998. "An Empirical Analysis of Consumer Decision Making Processes on Setting up Residential PV Systems." In J. Schmid and others, eds., *Proceedings of the Second World Conference and Exhibition on PV Solar Energy Conversion.* Report EUR 18656 EN. Brussels.

Lund, J.W. 1996. "Lectures on Direct Utilization of Geothermal Energy." Report 1996–1. United Nations University, Geothermal Training Programme, Reykjavik, Iceland.

Luyten, J.C. 1995. "Sustainable World Food Production and Environment." Research Institute for Agrobiology and Soil Fertility, Report 37. Agricultural Research Department, Wageningen, Netherlands.

Luzzi, A. 2000. "Showcase Project: 2 MW Demonstration Sole Thermal Power Plant." In *Proceedings of the 10th SolarPACES International Symposium of Solar Thermal Concentrating Technologies, Solar Thermal 2000.* March 8–10, Sydney.

Lynd, L.R. 1996. "Overview and Evaluation of Fuel Ethanol from Lignocellulosic Biomass: Technology, Economics, the Environment and Policy." *Annual Review of Energy and the Environment* 21: 403–65.

Mankins, J.C. 1998. "Power from Space: A Major New Energy Option?" Paper 4.1.16. Presented at the Proceedings of the 17th Congress of the World Energy Council. Houston, Tex.

Marrison, C.I., and E.D. Larson. 1995a. "Cost versus Scale for Advanced Plantation-based Biomass Energy Systems in the US." In *Proceedings of the EOA Symposium on Greenhouse Gas Emissions and Mitigation Research.* June 27–29, Washington, D.C.

———. 1995b. "A Preliminary Estimate for the Biomass Energy Production Potential in Africa for 2025." *Biomass and Bioenergy* 10 (5–6): 337–51.

Mathews, N. 1998a. "Changes for the Better on the Way." *Wind Power Monthly* 14 (5): 26–27.

———. 1998b. "Tax Evasion Scam Linked to Wind." *Wind Power Monthly* 14 (3): 26.

Matthies, H.G. and others. 1995. *Study of Offshore Wind Energy in the EC.* Brekendorf, Germany: Verlag Natürliche Energien.

Maycock, P.D. 1998. P*hotovoltaic Technology, Performance, Cost and Market Forecast: 1975–2010,* Version 7. Warrenton, Va.: Photovoltaic Energy Systems.

Meuleman, B., and A. Faaij. 1999. *Overview of Co-combustion Options for Coal Fired Power Plants.* Utrecht University, Deptartment of Science, Technology and Society, Netherlands.

Mills, D., and G. Morrison. 2000a. "Compact Linear Fresnel Reflector Solar Thermal Power Plants." *Source* 68 (3): 263–83.

———. 2000b. "Stanwell Solar Thermal Power Project."

MNCES (Ministry of Non-Conventional Energy Sources). 1999. *Annual Report 1990–2000.* Government of India.

Moore, E. A., and G. Smith. 1990. "Capital Expenditures for Electric Power in Developing Countries in the 1990s." Energy Series Paper, no. 21. World Bank, Washington, D.C.

Moore, T. 2000. "Renewed Interest for Space Solar Power." *EPRI Journal* (spring): 7–17.

Moreira, J. R., and A. D. Poole. 1993. "Hydropower and Its Constraints." In T. B. Johansson, H. Kelly, A.K.N. Reddy, R.H. Wiliams, and L. Burnham, *Renewable Energy: Sources for Fuels and Electricity.* Washington, D.C.: Island Press.

Morrison, G.L. 1999. "Packaged Solar Water Heating Technology, Twenty Years of Progress." In *Proceedings of the Solar World Congress.* Jerusalem.

Naber, J.E., F. Goudriaan, and A.S. Louter. 1997. "Further Development and Commercialisation of the Small Hydro-thermal Upgrading Process for Biomass Liquefaction." In *Proceedings of the Third Biomass Conference of the Americas.* Montreal.

National Laboratory. 1997. "Technology Opportunities to Reduce U.S. Greenhouse Gas Emissions – Appendix B – Technology Pathways Characteristics." Prepared for the U.S. Department of Energy [http://www.ornl.gov/climatechange].

Neij, L. 1999. "Dynamics of Energy Systems, Methods of Analysing Technology Change." Ph.D. diss., Lund University, Lund Institute of Technology, Sweden.

Nishimura, T. 1999. "Heat Pumps: Status and Trends in Asia and the Pacific." In *Proceedings of the 6th Heat Pump Conference.* Berlin.

NREL (National Renewable Energy Laboratory). 1999. [http://www.nrel.gov/otec].

NUTEK. 1996. *Energy in Sweden 1995.* Stockholm.

Oonk, H., J. Vis, E. Worrell, A. Faaij, and J.W. Bode. 1997. "The Methahydro Process: Preliminary Design and Cost Evaluation." TNO Report R 97/214. TNO Institute of Environmental Sciences, Energy Research and Process Innovation, Apeldoorn, Netherlands.

Osuna, R., V. Fernandez, M. Romero, and M. Blanco. 2000. "PS 10: A 10 Solar Power Evaluation Program." In *Proceedings of the 10th SolarPACES International Symposium of Solar Thermal Concentrating Technologies, Solar Thermal 2000.* March 8–10, Sydney.

Oud, E., and T.C. Muir. 1997. "Engineering and Economic Aspects of Planning, Design, Construction and Operation of Large Dam Projects." In T. Dorcey, ed., *Proceedings of the Workshop on 'Large Dams: Learning from the Past, Looking at the Future.'* IUCN, World Conservation Union, and World Bank Group; Gland, Switzerland; Cambridge, U.K. and Washington, D.C.

Pacheco, J., H. Reily, G. Kolb, and C. Tyner. 2000. "Summary of the Solar Two Test and Evaluation Program." In *Proceedings of the 10th SolarPACES International Symposium of Solar Thermal Concentrating Technologies, Solar Thermal 2000.* March 8–10, Sydney.

Patterson, W. 1999. *Transforming Electricity: The Coming Generation of Change.* Royal Institute of International Affairs. London: Earthscan.

PCAST (President's Committee of Advisors on Science and Technology). 1997. "Report to the President on Federal Energy Research and Development for the Challenges of the Twenty-first Century." Executive Office of the President of the United States, Panel on Energy Research and Development, Washington, D.C.

———. 1999. *Powerful Partnerships: The Federal Role in International Cooperation on Energy Innovation.* Executive Office of the President of the United States, Panel on International Cooperation in Energy Research, Development, Demonstration and Deployment, Washington, D.C.

Photon. 1999a. "The End of a Dream." *Photon* 1–99: 20–21.

———. 1999b. "World Ideas for PV Financing." *Photon* 1–99: 16–19.

Pikington. 1996. *Status Report on Solar Thermal Power Plants.* Cologne: Pikington Solar International.

Pratsch, L.W. 1996. "Geothermal, a Household Word by the Year 2000." *GRC Bulletin* 25: 25–31.

PVIR (Photovoltaic Insider's Report). 1999. *Photovoltaic Insider's Report.* 18 (2): 6.

Radja, V. 1997. "Strategy for Geothermal Energy Development in Indonesia Facing the Year 2000." In *Proceedings of NEDO International Geothermal Symposium.* Japan.

Randlov and others. 1994. "Final Report for JOULE Wave Energy Preliminary Actions." CEC DGXII, Brussels.

Rannels, J.E. 1998. Implementation and Financing for President Clinton's Million Solar Roofs Initiative. In J. Schmid and others, eds., *Proceedings of the Second World Conference and Exhibition on PV Solar Energy Conversion.* Report EUR 18656 EN. Brussels.

Ravindranath, N.H., and D.O. Hall. 1995. *Biomass, Energy and Environment: A Developing Country Perspective from India.* Oxford: Oxford University Press.

Rijk, P. 1994. *The Costs and Benefits of Willow (Salix) in Short Rotation for Niche Energy Markets in The Netherlands.* Agricultural Economics Institute (LEI-DLO), The Hague.

Rosillo-Calle, F., and L.A.B. Cortez. 1998. "Towards Pro-Alcool II: A Review of the Brazilian Bioethanol Programme." *Biomass and Bioenergy* 14 (2): 115–24.

Rosillo-Calle, F., M.A.A. de Rezende, P. Furtado, and D.O. Hall. 1996. *The Charcoal Dilemma: Finding a Sustainable Solution for Brazilian Industry*. Biomass Users Network. London: Intermediate Technology.

Rybach, L., and H.L. Goran. 1995. "Swiss Geothermal Energy Update." In *Proceedings the World Geothermal Congress 1995.*

Sastry, E.V.R. 1999. Personal communication. Ministry of Non-Conventional Energy Sources, Government of India.

Schainker, R.B. 1997 "Presentation to the PCAST Energy R&D Panel." Electric Power Research Institute, July 14. Palo Alto, Ca.

SERI (Solar Energy Research Institute). 1989. *Ocean Thermal Energy Conversion: An Overview.* SERI/SP-220-3024. Golden, Colo.

Shell. 1996. *The Evolution of the World's Energy Systems.* Shell International, Group External Affairs, London.

Solantausta, Y., T. Bridgewater, and D. Beckman. 1996. E*lectricity Production by Advanced Biomass Power Systems.* Espoo, Finland: VTT Technical Research Centre of Finland.

Spath, P., M. Mann, and W. Amos. 2000. "Comparison of Gasification Technologies for Converting Biomass to Hydrogen." Paper prepared for the First World Conference on Biomass and Industry, June 5–9, Seville, Spain.

Stassen, H.E. 1995. *Small Scale Biomass Gasification for Heat and Power Production: A Global Review.* World Bank Technical Paper 296, Energy Series. Washington, D.C.

Stefansson, V., and I.B. Fridleifsson. 1998. "Geothermal Energy: European and World-wide Perspective." Paper presented at expert hearing on assessment and prospects for geothermal energy in Europe. Parliamentary Assembly of the Council of Europe, Sub-Committee on Technology Policy and Energy, Strasbourg, France.

SunLab. 1999. "Parabolic Trough Technology Roadmap." http://www.eren.doe.gov/sunlab/TechOverview.htm

TERI. (Tata Energy Research Institute). 1996/97. *TERI Energy Data Directory and Yearbook.* New Delhi.

Thomas, G.T., H.N. Post, and R. DeBlasio. 1999. "Photovoltaic Systems: An End-of-Millennium Review." *Progress in Photovoltaics: Research and Applications* 7: 1–19.

TNO. 1992. *Aandachtspunten voor componentenonderzoek en alternatieve zonneboilerconcepten.* TNO B-92-0969. Delft, Netherlands.

Tolbert, V., ed. 1998. "Environmental Effects of Biomass Crop Production: What Do We Know, What Do We Need to Know?" *Biomass and Bioenergy* 14 (4): 301–414.

Tsuo, Y.S., J.M. Gee, P. Menna, D.S. Strebkov, A. Pinov, and V. Zadde. 1998. "Environmentally Benign Silicon Solar Cell Manufacturing." In J. Schmid and others, eds., *Proceedings of the Second World Conference on PV Solar Energy Conversion.* Report EUR 18656. Brussels.

Turkenburg, W.C. 1992. "On the Potential and Implementation of Wind Energy." In *Proceedings of the European Wind Energy Conference.* Vol. 2. Amsterdam: Elsevier.

Turnure, J.T., S. Winnett, R. Shackleton, and W. Hohenstein. 1995. "Biomass Electricity: Long Run Economic Prospects and Climate Policy Implications." In *Proceedings of the Second Biomass Conference of the Americas.* Portland, Or.

U.S. DOE (Department of Energy). 1998a.. *Renewable Energy Annual.* Washington, D.C.

———. 1998b. *Renewable Energy Technology Characterizations.* Office of Utility Technologies, Washington, D.C.

U.S. DOE (Department of Energy), OGT (Office of Geothermal Technologies). 1998. *Strategic Plan for the Geothermal Energy Program.* Washington, D.C.

Vaessen, P. 1997. “The Influence of Decentral Generation on Reliability (in Dutch). “ Hidde Nijland Symposium. Den Bosch, Netherlands.

van den Broek, R., and A. van Wijk. 1998. “Electricidad a partir de eucalipto y bagazo en ingenios azucareros de nicaragua: costos, aspectos macroeconomicos y medioambientales.” Documento de trabajo FOPW/99/2. Food and Agriculture Organization of the United Nations, Rome.

van den Broek, R., A. Faaij, and A. van Wijk, 1996. “Biomass Combustion Power Generation Technologies.” *Biomass and Bioenergy* 11 (4): 271–81.

van den Broek, R., A. Faaij, A.J.M. van Wijk, T. Kent, M. Bulfin, K. Healion, and G. Blaney. 1997. “Willow Firing in Retrofitted Irish Power Plants.” *Biomass and Bioenergy* 12 (2): 75–90.

van der Leun, C. “Environmental Aspects of Material Use of SDHW Systems” (in Dutch). Utrecht, Netherlands: Ecofys.

Wijk, A.J.M. van, N. Halberg, and W.C. Turkenburg. 1992. “Capacity Credit of Wind Power in the Netherlands.” *Electric Power Systems Research* 23 (3): 189–200.

Vasquez, N.C., and S.P. Javellana. 1997. “Present and Future Geothermal Development in the Philippines.” In *Proceedings of the NEDO International Geothermal Symposium.* Sendai, Japan.

Verhoeven, S. 1999. “Two-way Traffic in the Electricity Grid and the Role of Power Electronics (in Dutch).” Paper presented at the STT Symposium Rapid Current: The Next Wave of Electrical Innovation, February 25, The Hague, Netherlands.

Voskens, R.G.J.H., and S. Carpenter. 1999. “Potential for Solar Drying in the World.” Enermodal engineering, Canada / Ecofys, The Netherlands.

Walter, A., M.R. Souza, and R.P. Overend. 1998. “Preliminary Evaluation of Co-firing Biomass (Sugar-Cane Residues) and Natural Gas in Brazil.” State University of Campinas, Mechanical Engineering College, Energy Division, Brazil; and National Renewable Energy Laboratory, Golden, Colo.

WEC (World Energy Council). 1994a. *Energy for Toworrow’s World.* London: Kogan Page.

———. 1994b. *New Renewable Energy Resources: A Guide to the Future.* London: Kogan Page.

———. 1998. *Survey of Energy Resources 1998.* London.

Weinberg, C. 1995. “A New Age for Electricity: Integrating Technology into Business and Strategy.” UNIPEDE (International Union of Producers and Distributors of Electric Energy), International Electrical Research Exchange, Monte-Carlo, Monaco.

Weise, E., R. Klockner, R. Kniehl, Ma Shenghong, and Qin Jianping. 1995. “Remote Power Supply Using Wind and Solar Energy: A Sino-German Technical Co-operation Project.” In *Proceedings of the Beijing International Conference on Wind Energy.* Beijing.

Wentzel, M. 1995. “Solar Cooking: Problems, Perspectives and Possibilities.” *In Proceedings Solar World Congress.* Harare, Zimbabwe.

Williams, R.H., and E.D. Larson. 1996. Biomass Gasifier Gas Turbine Power Generating Technology.” *Biomass and Bioenergy* 10 (2–3): 149–66.

Williams, R.H., E.D. Larson, R.E. Katofsky, and J. Chen. 1995. “Methanol and Hydrogen from Biomass for Transportation, with Comparisons to Methanol and Hydrogen from Natural Gas and Coal.” Princeton University, Centre for Energy and Environmental Studies, Princeton, N.J.

Winkelman, J.E. 1992. “De invloed van de SEP proef-windcentrale te Oosterbierum op Vogels: Aanvaringsslachtoffers.” RIN-rapport 92/2. DLO-instituut voor Bos-en Natuuronderzoek, Arnhem, Netherlands.

Wiser, R., and Pickle S. 1997. “Financing Investments in Renewable Energy: The Role of Policy Design and Restructuring.” Report LBNL-39826. Lawrence Berkeley National Laboratory, Environmental Energy Technologies Division, Calif.

World Atlas. 1998. 1998 World Atlas and Industry Guide. International Journal on Hydropower and Dams. Aqua-Media International, Sutton, U.K.

WRR (Wetenschappelijke Raad voor het Regeringsbeleid). 1992. *Ground for Choices: Four Perspectives for the Rural Areas in the European Community.* The Hague: Sdu uitgeverij.

Wyman, C.E., R.L. Bain, N.D. Hinman, and D.J. Stevens. 1993. “Ethanol and Methanol from Cellulosic Biomass.” In T.B. Johansson J.H. Kelly, A.K.N. Reddy, R.H. Wiliams, and L. Burnham, *Renewable Energy: Sources for Fuels and Electricity.* Washington, D.C. Island Press.

YY. 1998. *Proceedings: Third European Wave Power Conference.* September–October, Patras,Greece.