# Understanding Renewable Energy Systems

Volker Quaschning

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For a full list of publications please contact:
Earthscan
8–12 Camden High Street
London, NW1 0JH, UK
Tel: +44 (0)20 7387 8558
Fax: +44 (0)20 7387 8998
Email: earthinfo@earthscan.co.uk
Web: **www.earthscan.co.uk**

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# List of Acronyms and Abbreviations

| | |
|---|---|
| AC | alternating current |
| AM | air mass |
| BTU | British thermal unit |
| CB | conduction band |
| CET | Central European Time |
| CFCs | chlorofluorocarbons |
| CHP | combined heat and power |
| CIS | copper indium diselenide |
| COP | coefficient of performance |
| CPI | consumer price index |
| CVD | chemical vapour deposition |
| DC | direct current |
| EG-Si | electronic-grade silicon |
| EPDM | ethylene propylene diene monomer |
| ESTIF | European Solar Thermal Industry Federation |
| EVA | ethylene vinyl acetate, |
| FB | forbidden band |
| FF | fill factor |
| GMT | Greenwich Mean Time |
| GTO | gate turn off |
| GUT | Greenwich Universal Time |
| HDR | hot dry rock method |
| IC | integrated circuit |
| ICS | integral collector storage |
| IEA | International Energy Agency |
| IGBT | insulated gate bipolar transistors |
| IPCC | Intergovernmental Panel on Climate Change |
| IR | infrared reflecting |
| kg ce | kg coal equivalent |
| kg oe | kg oil equivalent |
| LCV | lower calorific value |
| LEC | levelled electricity cost |
| LHC | levelled heat cost |
| MCA | maximum credible accident |
| MCFC | molten carbonate fuel cell |
| MET | Mean European Time |
| MG-Si | metallurgical grade silicon |
| MIS | metal–insulator–semiconductor |
| MLT | Mean Local Time |

| | |
|---|---|
| MOSFET | metal oxide semiconductor field effect transistor |
| MPP | maximum power point |
| NaS | sodium–sulphur |
| NiCd | nickel–cadmium |
| NiMH | nickel–metal hydride |
| NPV | net present value |
| PAFC | phosphoric acid fuel cell |
| PE | polyethylene |
| PP | polypropylene |
| ppm | parts per million |
| ppmv | parts per million by volume |
| PR | performance ratio |
| PR | progress ratio (Chapter 6) |
| PST | Pacific Standard Time |
| PV | photovoltaic |
| PWM | pulse-width modulation |
| R&D | research and development |
| rms | root mean square |
| SEGS | solar electric generation system |
| SOC | state of charge |
| SOFC | solid oxide fuel cell |
| SOG-Si | solar grade silicon |
| sr | steradian |
| STC | standard test conditions |
| TIM | transparent insulation material |
| UCV | upper calorific value |
| UNEP | United Nations Environmental Programme |
| UNFCCC | United Nations Framework Convention on Climate Change |
| VB | valence band |
| VDEW | Vereinigung Deutscher Elektrizitätswerke |
| VDI | Verein Deutscher Ingenieure |
| WMO | World Meteorological Organisation |

# Preface

The destruction of the environment and global warming are among the problems first mentioned in many public opinion polls that ask what are the major problems to be solved in this century. Today's energy supply is largely responsible for the anthropogenic greenhouse effect, acid rain and other negative impacts on health and the environment. The current trend is clearly not sustainable, especially given the enormous demand for energy predicted for the future. Several energy sources, however, offer the opportunity to cover our energy demand sustainably, i.e. with almost no negative influence on health and nature. These are also called renewable energy systems, because the 'fuel' is replenished by nature.

This textbook is based on the German book *Regenerative Energiesysteme*, which was first published in 1998 and became a standard text used at German universities in courses on renewable energy. Two editions have sold out and the third edition came out in 2003.

The book is aimed mainly at students, engineers, researchers and others with technical interests wanting to obtain a basic knowledge of renewable energy production. It describes the most important technical systems for using renewable energy sources, and introduces important calculation and simulation methods for these. The main focus is on technologies with high development potentials such as solar thermal systems, photovoltaics and wind power.

When describing renewable energy subjects, one has to consider technical descriptions as well as the impact on today's energy supply or sociopolitical backgrounds. A compromise between socioeconomic and technical issues must be found when dealing with energy matters. A textbook with technical focus has the obligation to describe technologies in an objective manner. However, the author's subjective influence can never be avoided entirely. The choice of contents, methods of data presentation and even the subjects left out of the book are already based on opinions.

Therefore, this book consciously renounces separation of the technological aspects from any consequences of using the technologies, or from sociopolitical aspects. The intention is to emphasize that engineers must bear in mind the potential negative impacts of the use of developed technologies. Otherwise they must accept the heavy responsibility of allowing those impacts to occur.

Those in engineering circles are often of the opinion that the development of technology itself cannot have negative consequences. It is the use of a technology that would create such consequences. However, it is irresponsible to search for technical innovations only for the sake of improving technology. The consequences of many new or even well established technologies are very difficult to estimate in many cases. Therefore, all who are involved in the development, production and application of a technology are responsible for predicting consequences critically and warning of possible dangers in time. With the aim of acknowledging this responsibility, this book always tries to point out negative consequences besides description of facts.

From my experience as a professor in the education sector, I know that the majority of people who are interested in renewable energy technologies deals intensively with the consequences of the conventional energy supply. A linking of technical with sociopolitical contents is often desired implicitly. Therefore, this textbook does not only describe technological aspects, but also deals consciously with problems of the energy industry in Chapters 1 and 6. Here, great importance was attached to substantiating all statements with objective and up-to-date facts. This allows all readers to form their own opinion.

Interesting discussions while writing this book and the very positive feedback on the German version of this book were especially motivating for me. They have shown that problems that go beyond purely technical questions are seen as very important. These problems are often ignored because they question our way of life. Solutions are difficult but not impossible to find. Constructive discussions are the first step. I hope this book can provide a contribution to such a discussion.

*Volker Quaschning*
*Berlin, Summer 2004*

Chapter 1

# Energy, Climate Change and Renewable Energy Sources

## THE EXPRESSION 'ENERGY'

The expression 'energy' is often used without a great deal of thought and is applied to very different contexts. In this textbook – which only deals with technically usable types of energy, especially renewables – the physical laws describing the utilization of the energy resources will be investigated. Power is inseparably linked with energy. Since many people mix up energy, work and power, the first part of this chapter will point out differences between these and related quantities.

In general, energy is the ability of a system to cause exterior impacts, for instance a force across a distance. Input or output of work changes the energy content of a body. Energy exists in many different forms such as:

- mechanical energy
- potential energy
- kinetic energy
- thermal energy
- magnetic energy
- electrical energy
- radiation energy
- nuclear energy
- chemical energy.

According to the definition above, a litre or gallon of petrol is a potential source of energy. Petrol burned in an internal combustion engine moves a car of a given mass. The motion of the car is a type of work. Heat is another form of energy. This can be seen when observing a mobile turning in the hot air ascending from a burning candle. This motion clearly demonstrates the existing force. Wind contains energy that is able to move the blades of a rotor. Similarly, sunlight can be converted to heat, thus light is another form of energy.

The *power*:

$$P = \frac{\mathrm{d}W}{\mathrm{d}t} = W \qquad (1.1)$$

**Table 1.1** *Conversion Factors for Energy*

| | *kJ* | *kcal* | *kWh* | *kg ce* | *kg oe* | *m³ gas* | *BTU* |
|---|---|---|---|---|---|---|---|
| 1 kilojoule (kJ) | 1 | 0.2388 | 0.000278 | 0.000034 | 0.000024 | 0.000032 | 0.94781 |
| 1 kilocalorie (kcal) | 4.1868 | 1 | 0.001163 | 0.000143 | 0.0001 | 0.00013 | 3.96831 |
| 1 kilowatt-hour (kWh) | 3600 | 860 | 1 | 0.123 | 0.086 | 0.113 | 3412 |
| 1 kg coal equivalent (kg ce) | 29,308 | 7000 | 8.14 | 1 | 0.7 | 0.923 | 27,779 |
| 1 kg oil equivalent (kg oe) | 41,868 | 10,000 | 11.63 | 1.428 | 1 | 1.319 | 39,683 |
| 1 m³ natural gas | 31,736 | 7580 | 8.816 | 1.083 | 0.758 | 1 | 30,080 |
| 1 British Thermal Unit (BTU) | 1.0551 | 0.252 | 0.000293 | 0.000036 | 0.000025 | 0.000033 | 1 |

is the first derivative of the work, *W*, with respect to the time, *t*. Thus, power describes the period of time in which the correlated work is performed. For instance, if a person lifts a sack of cement 1 metre, this is work. The work performed increases the kinetic energy of the sack. Should the person lift the sack twice as fast as before, the period of time is half. Hence the power needed is twice that of before, even if the work is the same.

The units of both energy and work according to the SI unit system are joules (J), watt seconds (Ws) or newton metres (Nm), and the unit of power is the watt (W). Besides SI units a few other units are common in the energy industry. Table 1.1 shows conversion factors for most units of energy in use today. Older literature uses antiquated units such as kilogram force metre kpm (1 kpm = $2.72 \cdot 10^{-6}$ kWh) or erg (1 erg = $2.78 \cdot 10^{-14}$ kWh). Physics also calculates in electronvolts (1 eV = $4.45 \cdot 10^{-26}$ kWh). The imperial unit BTU (British Thermal Unit, 1 BTU = 1055.06 J = 0.000293071 kWh) is almost unknown outside the US and the UK. Common convention is to use SI units exclusively; this book follows this convention apart from using electronvolts when describing semiconductor properties.

Many physical quantities often vary over many orders of magnitudes; prefixes help to represent these and avoid using the unwieldy exponential notation. Table 1.2 summarizes common prefixes.

Errors often occur when working with energy or power. Units and quantities are mixed up frequently. However, wrong usage of quantities can change statements or cause misunderstandings.

For example, a journal article was published in the mid-1990s in Germany describing a private photovoltaic system with a total installed power of 2.2

**Table 1.2** *Prefixes*

| *Prefix* | *Symbol* | *Value* | *Prefix* | *Symbol* | *Value* |
|---|---|---|---|---|---|
| Kilo | k | $10^3$ (thousand) | Milli | m | $10^{-3}$ (thousandth) |
| Mega | M | $10^6$ (million) | Micro | $\mu$ | $10^{-6}$ (millionth) |
| Giga | G | $10^9$ (billion) | Nano | n | $10^{-9}$ (billionth) |
| Tera | T | $10^{12}$ (trillion) | Pico | p | $10^{-12}$ (trillionth) |
| Peta | P | $10^{15}$ (quadrillion) | Femto | f | $10^{-15}$ (quadrillionth) |
| Exa | E | $10^{18}$ (quintillion) | Atto | a | $10^{-18}$ (quintillionth) |

*Note:* Words in parentheses according to US numbering system

kW. It concluded that the compensation of €0.087 to be paid per kW for feeding into the public grid was very low. Indeed, such a subsidy would be very low: it would have been 2.2 kW · €0.087/kW = €0.19 in total because it was stated as a subsidy for installed power (unit of power = kW). Although subsidies to be paid for solar electricity were quite low at that time, no owner of a photovoltaic system in Germany got as little as a total of 20 Eurocents. The author should have quoted that the payment per kilowatt *hour* (kW*h*) for electricity fed into the grid was €0.087. Assuming that the system would feed 1650 kWh per year into the grid, the system owner would get €143.55 per year. This is 750 times more than the compensation on the power basis. This example demonstrates clearly that a missing 'h' can cause significant differences.

Physical laws state that energy can neither be produced nor destroyed or lost. Nevertheless, many people talk about energy losses or energy gains, although the *law of energy conservation* states:

> *The energy content of an isolated system remains constant. Energy can neither be destroyed nor be created from nothing; energy can transform to other types of energy or can be exchanged between different parts of the system.*

Consider petrol used for moving a car: petrol is a type of stored chemical energy that is converted in a combustion engine to thermal energy, which is transformed by the pistons into kinetic energy for the acceleration of the car. Stopping the car will not destroy this energy. It will be converted to potential energy if the car climbed a hill, or to ambient heat in the form of waste heat from the engine or frictional heat from tyres, brakes and air stream. Normally, this ambient heat cannot be used anymore. Thus, driving a car converts the usable chemical energy of petrol into worthless ambient heat energy. This energy is lost as useful energy but is not destroyed. This is often paraphrased as energy loss. Hence, 'energy loss' means converting a high quality usable type of energy to a low quality non-usable type of energy.

An example illustrating the opposite is a photovoltaic system that converts sunlight to electricity. This is often described as producing energy, which, according to the law of energy conservation, is not possible. Strictly speaking,

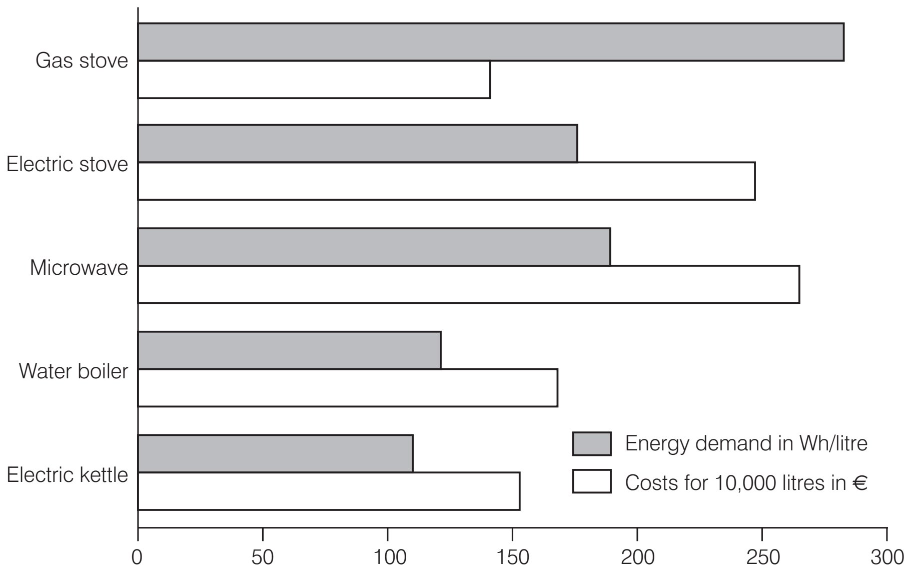



**Figure 1.1** *Prices for Water Heating*

a part of the energy in the incident solar radiant energy is converted to electrical energy, i.e. the photovoltaic system converts non-usable energy to high quality energy.

Technical systems perform energy conversions with varying efficiencies. The following example should illustrate this.

The *thermal energy*, $Q$, which is needed to heat up one litre of water (mass $m = 1$ kg) from the temperature $\vartheta_1 = 15°C$ to $\vartheta_2 = 98°C$ is calculated with the heat capacity, $c$, of water $c_{H_2O} = 4187$ kJ/(kg K) using:

$$Q = c \cdot m \cdot (\vartheta_2 - \vartheta_1) \tag{1.2}$$

to $Q = 348$ kJ $= 97$ Wh.

A consumer magazine has compared different systems for boiling water. Figure 1.1 shows the results of different electrical appliances and compares them with those from a gas stove. The graph seems to show that the gas stove has the highest energy consumption while the energy costs are the lowest. The explanation is not the low price of gas, but that the graph compares different energy sources.

The electric stove uses electrical energy for water heating. Normally, this type of energy does not exist in nature, except for lightning or in electric eels. Power stations convert primary energy sources such as coal, gas or uranium into useful electricity. Conventional power stations produce large amounts of waste heat, which is emitted into the environment. They convert only a fraction of the energy stored in coal, gas or uranium into electricity, and the

**Table 1.3** *Primary Energy, Final Energy and Effective Energy*

| *Term* | *Definition* | *Type of energy or energy source* |
|---|---|---|
| Primary energy | Original energy, not yet processed | e.g. crude oil, coal, uranium, solar radiation, wind |
| Final energy | Energy in the form that reaches the end user | e.g. gas, fuel oil, petrol, electricity, hot water or steam |
| Effective energy | Energy in the form used by the end user | e.g. light, radiator heat, driving force of machines or vehicles |

majority is 'lost'. The *efficiency*, $\eta$, describes the conversion quality and is given by:

$$\textit{efficiency } \eta = \frac{\textit{profitable energy}}{\textit{expended energy}} \tag{1.3}$$

The average thermal power station in countries such as Germany has an efficiency of around 34 per cent. Two thirds of the expended energy disappears as waste heat. This means that only one third remains as electricity.

Technical conversion of energy has different conversion stages: primary energy, final energy and effective energy. These stages are explained in Table 1.3.

Going back to the example, it has to be emphasized that the calculated thermal energy (see equation (1.2)) is the effective energy, and the values given in Figure 1.1 are final energy. The comparison of energy efficiency should, instead, be based on primary energy when considering different energy carriers such as gas and electricity. The primary energy source for generating electricity is the coal, gas or uranium used in conventional power plants. Natural gas used for boiling water is also a type of final energy. The transport of natural gas to the consumer causes some losses, but these are much lower than the

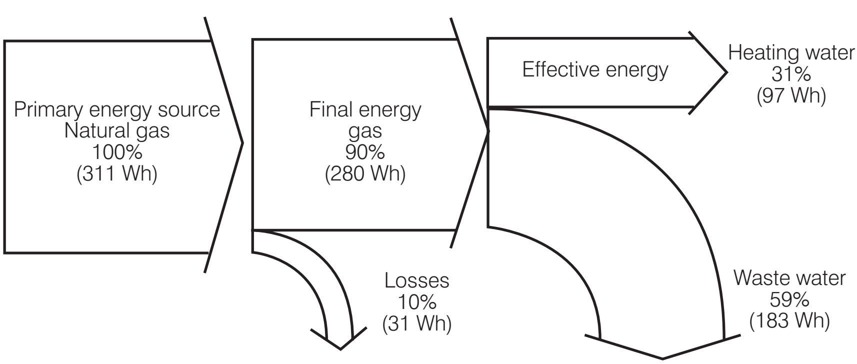



**Figure 1.2** *Energy Conversion Chain and Losses for Water Heating with a Gas Cooker*

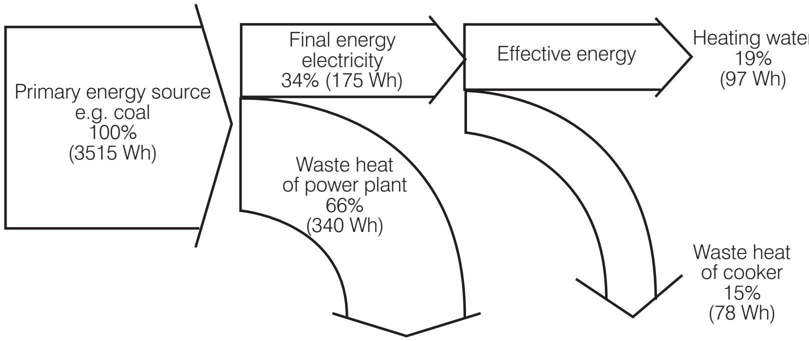



**Figure 1.3** *Energy Conversion Chain and Losses for Water Heating with an Electric Cooker*

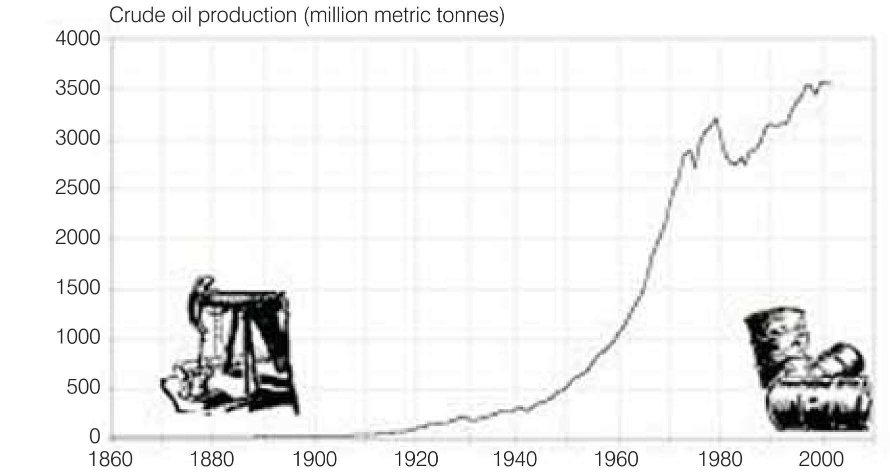
losses of the electrical transmission system (see Figure 1.2). Therefore, the primary energy consumption of the electric stove of 515 Wh = 1980 kJ is 65 per cent higher than that of the gas stove, although the final energy consumption is more than 30 per cent below that of the gas stove. This example is summarized in Figures 1.2 and 1.3, in which the energy conversion chain is compared for the electric and gas stove. The gas stove is the most economical appliance when comparing the primary energy demand, and it is the primary energy demand that determines the environmental impact.

## Evolution of World Energy Demand

Coal and crude oil were not relevant as energy supplies at the end of the 18th century. Firewood and techniques for using wind and hydro power provided the entire energy demand. Watermills and windmills were common features of the landscape during that time.

In 1769 James Watt laid the foundations for industrialization by developing the steam engine. The steam engine, and later the internal combustion engine, swiftly replaced mechanical wind and water installations. Coal became the single most important source of energy. In the beginning of the 20th century, crude oil took over as it was needed to support the increasing popularity of motorized road traffic. Firewood lost its importance as an energy supply in the industrial nations, and large hydro-electric power stations replaced the watermills.

The world energy demand rose sharply after the Great Depression of the 1930s. Natural gas entered the scene after World War II. In the 1960s, nuclear power was added to the array of conventional energy sources. These relatively new sources have not yet broken the predominance of coal and crude oil, but gas is the energy carrier with the fastest growth. The share of nuclear electricity of today's primary energy demand is still relatively low. The fossil energy sources – coal, crude oil and natural gas – provide more than 85 per cent of the world primary energy demand.




*Source:* BP, 2003; IEA, 2003a

**Figure 1.4** *Evolution of Annual Crude Oil Production*

Figure 1.4 shows the annual oil production, illustrating the enormous increase in world energy consumption. One million metric tonnes of crude oil have an energy content of about 42 PJ or $42 \cdot 10^{15}$ J. Production rates increased exponentially after World War II. Two oil crises, in 1973 and 1978, slowed down this development, holding back the development of world economic growth and the energy demand until 1982.

Table 1.4 shows the *world primary energy consumption* of different energy sources over much of the last century. The estimation of primary energy equivalents for nuclear electricity and hydro-electricity is inconsistent; the majority of the newer statistics multiply the electricity output of nuclear power stations by 2.6 or 3 to obtain the primary energy demand. This considers the conversion efficiency of thermal power plants to be 38 per cent, or 33 per cent. The efficiency of hydro-electric power plants is much higher and can even reach values of 90 per cent or more. Since the real efficiency of hydro-electric power plants is difficult to estimate during operation, some statistics define the output as primary electricity and assume an efficiency of 100 per cent. Thus, hydro-electric power plants need much less primary energy than nuclear power plants to produce the same amount of electricity. However, statistics comparing the world primary energy supply of nuclear power plants (multiplied by 2.6 or 3) with that of hydro-electric power plants (multiplied by 1) give the impression that the hydro-electricity share is much less than that of nuclear electricity, although the world electricity supply of both is similar. Table 1.4 does not contain other renewable energy sources such as biomass (e.g. firewood and vegetable waste), wind energy, solar energy and geothermal energy. The section in this chapter (p19) on global use of renewable energy resources will describe the contribution of renewable energy.

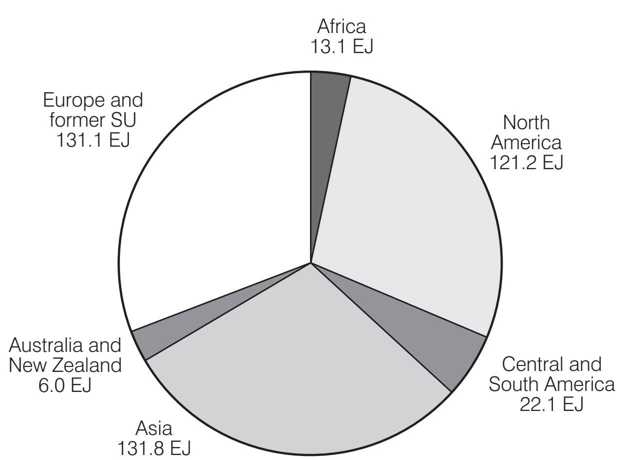
**Table 1.4** *World Primary Energy Consumption Excluding Biomass and Others*

| *In PJ* | *1925* | *1938* | *1950* | *1960* | *1968* | *1980* | *2002* |
|---|---|---|---|---|---|---|---|
| Solid fuels[a] | 36,039 | 37,856 | 46,675 | 58,541 | 67,830 | 77,118 | 100,395 |
| Liquid fuels[b] | 5772 | 11,017 | 21,155 | 43,921 | 79,169 | 117,112 | 147,480 |
| Natural gas | 1406 | 2930 | 7384 | 17,961 | 33,900 | 53,736 | 95,543 |
| Hydro-electric power[c] | 771 | 1774 | 3316 | 6632 | 10,179 | 16,732 | 24,792 |
| Nuclear power[c] | 0 | 0 | 0 | 0 | 463 | 6476 | 25,564 |
| Total | 43,988 | 53,577 | 78,530 | 127,055 | 191,541 | 271,174 | 393,773 |

*Note:* a Hard coal, lignite, etc.; b oil products; c converted on the basis of thermal equivalence assuming 38 per cent conversion efficiency
*Source:* Enquete-Kommission, 1995; BP, 2003

The global energy demand will continue to increase in the foreseeable future. It is anticipated that the increase in the industrialized nations will be lower than in developing countries, which are nonetheless catching up with the industrialized world. Furthermore, the world population is set to grow in the next few decades. Studies predict that by 2050 the energy demand will increase by a factor of 2.3 to 4 compared to 1990 (IPCC, 2000) (see also Table 1.17). This will intensify the problems of today's already high energy consumption and its consequences, such as the greenhouse effect and the rapid depletion of fossil energy resources.

The energy demand of the continents is totally different as shown in Figure 1.5. The primary energy demand of Europe, Asia and the US is certainly of the same order of magnitude. However, the population in Asia is six times that of Europe and ten times higher than that of the US. Today, the highly populated




*Source:* DOE, 2003

**Figure 1.5** *World Primary Energy Demand by Region in 2001*

**Table 1.5** *Fossil Fuel Reserves*

| | *Crude oil* | *Natural gas* | *Coal* |
|---|---|---|---|
| Proven reserves[a] | 142.7 billion t ≡ 5975 EJ | 155.8 billion $m^3$ ≡ 4944 EJ | 984 billion t ≡ 28,852 EJ |
| Production in 2002 | 3.56 billion t ≡ 149 EJ | 2.53 billion $m^3$ ≡ 80 EJ | 4.82 billion t ≡ 141 EJ |
| Reserves/production ratio[a] | 41 years | 61 years | 204 years |
| Unproven additional reserves[b] | 84 billion t | 217 billion $m^3$ | 6668 billion t[c] |
| Accumulated production[b] | 128.2 billion t | 69.6 billion $m^3$ | – |

*Note:* a At the end of 2002; b at the end of 2001; c total reserves;
1 t = 1 metric tonne = 2204.62 lb = 1.1023 short tonnes
*Source:* BP, 2003; BGR, 2002

and less-developed continents, South America and Africa, have a very small portion of the world primary energy demand. The section headed 'Greenhouse Effect' (see p10), will illustrate this uneven distribution of the energy demand by looking at the per capita carbon dioxide emissions, which correlate strongly with the energy demand.

## Reserves of Fossil Energy Sources

The current energy supply depends mainly on fossil energy carriers as described in the previous section. Fossil fuels such as natural gas, petroleum, hard and brown coal needed many thousands of years to form. Organic substances (i.e. animal or vegetable residues) were the base materials. Hence, fossil fuels are stored biomass of the ancient past. A huge amount of these fossil fuels has already been consumed in the 20th century. However, due to the increasing exploitation of the fossil reservoirs, future extraction will be more and more difficult, technically challenging and risky and therefore much more expensive than today. Deep-sea oil rigs are one step in this development. If fossil fuel use continues unchecked, all available reserves of petroleum and natural gas will be exploited within the 21st century (BP, 2003). Only coal reserves will be available for a longer period of time (see Table 1.5). Thus, some decades from now, a few generations of humanity will have exploited the whole fossil energy reserves that required millions of years to form. Future generations will no longer have the opportunity to use fossil fuels as their energy supply.

An exact estimation of the existing reserves of fossil energy resources is very difficult, because only the size of deposits already explored is known. Additional reserves to be discovered in future can only be estimated. However, even if major fossil fuel reserves should be discovered, this would not change the fact that fossil fuel reserves are limited. The time span of their availability can be extended only by some years or decades at best.

**Table 1.6** *Uranium (U) Resources for 2001*

| | Resources with production costs US$40/kg U | US$40–130/kg U | Total |
|---|---|---|---|
| Resources | 1.57 Mt[a] | 5.67 Mt[b] | 7.24 Mt ≡ 3620 EJ |
| Speculative resources | 12.52 Mt | | 12.52 Mt ≡ 6260 EJ |

*Note:* a Reasonable assured resources; b reasonable assured resources and estimated additional resources
*Source:* BGR, 2002

When dealing with energy reserves, proven reserves are most important. These are reserves available with certainty, which have been proven by exploration through drilling and measurement and which are technically and economically exploitable. Additionally, unproven reserves of uncertain extent exist, but are hard to estimate. Dividing the proven reserves of an energy carrier by the present annual demand provides the statistical duration of the reserve. This duration will decrease if the energy demand rises and will increase if new reserves are exploited.

The Earth's uranium reserves for operating nuclear power stations are limited as well. The estimated global reserves are less than 20 million t, of which 12.52 million t are only speculative. Table 1.6 shows the uranium reserves. At present, only about 5 per cent of the global energy demand is provided by nuclear energy. If the total world primary energy demand in 2000, about $1.1 \cdot 10^{14}$ kWh ≈ 400 EJ, had been provided by nuclear power, the reasonably assured, economically exploitable reserves would have lasted only about 2 years. Breeder reactors can increase this time by a factor of about 60. However, nuclear power on the basis of nuclear fission is no real long-term alternative to fossil fuels due to the very restricted reserves of uranium.

Only a limited number of today's technologies will survive the 21st century due to very limited reserves of conventional energy carriers. This fact is a sufficient reason to switch our present energy supply to non-fossil and non-nuclear energy sources. This development should be completed before the conventional energy reserves are depleted. The next two sections will describe two additional motivations for a change in energy policy: the greenhouse effect and the risks of nuclear power.

## Greenhouse Effect

Without the protection of Earth's atmosphere, the global mean ambient temperature would be as low as –18°C. Particular gases in the atmosphere such as carbon dioxide ($CO_2$), water vapour and methane capture parts of the incoming solar radiation, acting like a greenhouse. These gases have natural as well as anthropogenic, or human-induced, sources. Figure 1.6 illustrates the anthropogenic greenhouse effect.

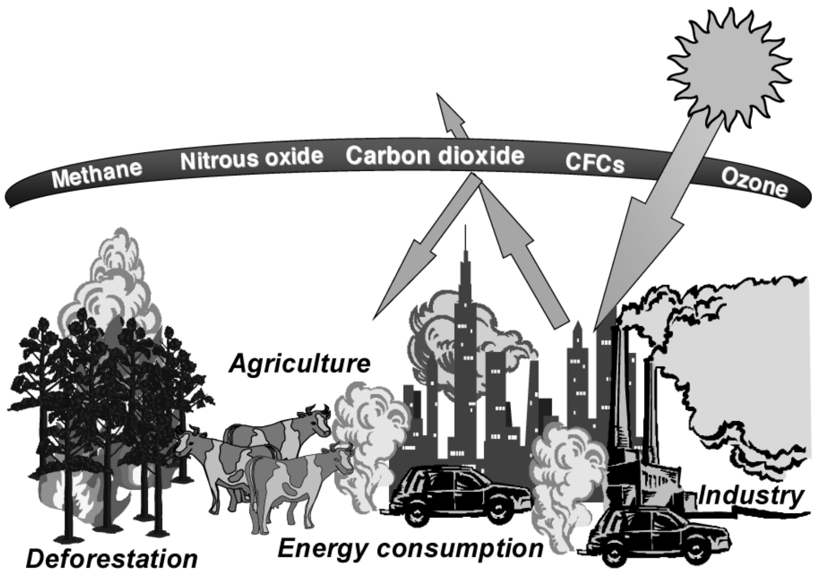



**Figure 1.6** *Origin of the Anthropogenic (Human-induced) Greenhouse Effect*

The existing *natural greenhouse effect* makes life on Earth possible. Without the natural greenhouse effect, Earth would emit most of its heat radiation into space. Incident sunlight heats the Earth's surface, and the mean global ambient temperature is roughly +15°C due to the retention of this heating energy.

Over millions of years, nature has created a balance in the concentration of atmospheric gases. This has made life as we know it today possible. Several natural temperature variations have occurred over the preceding millennia, as evidenced by different ice ages.

Additional greenhouse gases are emitted to the atmosphere as a result of energy consumption and other human-induced influences. These gases cause the anthropogenic greenhouse effect. Table 1.7 summarizes the characteristics of the most important greenhouse gases.

Anthropogenic *carbon dioxide* ($CO_2$) results from burning fossil fuels and biomass. It contributes 61 per cent to the greenhouse effect and is the most relevant greenhouse gas. Biomass is carbon dioxide neutral if it is used at the same rate as it is grown again. On the other hand, fire clearing in the rain forest produces vast amounts of $CO_2$ that has been bound by these plants over decades or centuries and thus can be considered a contributor to the greenhouse effect. However, the burning of fossil fuels emits the largest amount of anthropogenic carbon dioxide. The share of fossil fuel-related carbon dioxide emissions is currently 75 per cent, and is increasing. The carbon dioxide concentration in the outer atmosphere has already risen from 280

**Table 1.7** *Characteristics of Greenhouse Gases in the Atmosphere in 1998*

| *Greenhouse gas* | $CO_2$ | $CH_4$ | $N_2O$ | $O_3$ | *CFC-11* | *HFC-23* |
|---|---|---|---|---|---|---|
| Concentration in ppm | 365 | 1.745 | 0.314 | 0.03 | 0.000268 | 0.000014 |
| Atmospheric lifetime in years | 5–200 | 12 | 114 | 0.1 | 45 | 260 |
| Rate of concentration change in %/year | 0.4 | 0.4 | 0.25 | 0.5 | –0.5 | 3.9 |
| Specific global warming potential | 1 | 32 | 150 | 2000 | 14,000 | 10,000 |
| Global warming share in % | 61 | 15 | 4 | <9 | 11 (all fluorocarbons) | |

*Source:* IPCC, 2001

ppmv (parts per million by volume) in 1850 to 372 ppmv in 2002 (Blasing and Jones, 2003). If there is no change in energy policy, this development will accelerate in the coming decades. Today's carbon dioxide concentration in the atmosphere is already higher than at any other time during the past 250,000 years.

Anthropogenic *methane* ($CH_4$) sources are coal mining, production of natural gas, waste disposal and agriculture such as cattle farming or cultivation of rice. The production and use of fossil fuels causes the majority of methane emissions. Although the concentration of methane in the atmosphere is less than 1 per cent of the carbon dioxide concentration, methane has a high climate change potential (15 per cent contribution to the greenhouse effect), i.e. the global warming potential of methane is much higher than that of carbon dioxide. Therefore, much smaller emission quantities are critical. In 1998 the average tropospheric concentration of 1.745 ppmv of methane had already more than doubled compared to the pre-industrial concentration of 0.7 ppmv.

*Chlorofluorocarbons* (CFCs) have been used in large quantities as refrigerants or propellants in spray cans. CFCs fell into disrepute mainly due to their destructive influence on the ozone layer in the stratosphere at a height of 10–50 km. International agreements to reduce CFC production in a step-by-step process initially slowed down the increase and finally decreased the concentration in recent years. However, the greenhouse potential of CFCs (11 per cent contribution to the greenhouse effect) was no significant argument in the CFC reduction discussions. Some substitutes for CFCs such as HFC-23 or R134a have significantly lower ozone-destroying potential but nearly the same greenhouse potential.

Fire clearance of tropical rain forests and the use of nitrogenous fertilizers are sources of anthropogenic *nitrous oxide* ($N_2O$). In 2001 the atmospheric $N_2O$ concentration of 0.317 ppmv was only 16 per cent above the pre-industrial value; however, nitrous oxide also has a critical influence on climate change since it has a relatively long atmospheric residual time.

Motorized road traffic using fossil fuels also causes pollutants responsible for the formation of ground level *ozone* ($O_3$). Human-induced *stratospheric water vapour* ($H_2O$) also influences the greenhouse effect. However, the extent of the impact of these gases and other gases is difficult to estimate.

The contribution of different sources to the anthropogenic greenhouse effect can be summarized as:

- use of fossil fuels — 50 per cent
- chemical industry (CFCs, halons) — 20 per cent
- destruction of tropical rain forests (fire clearance, rotting) — 15 per cent
- agriculture — 15 per cent

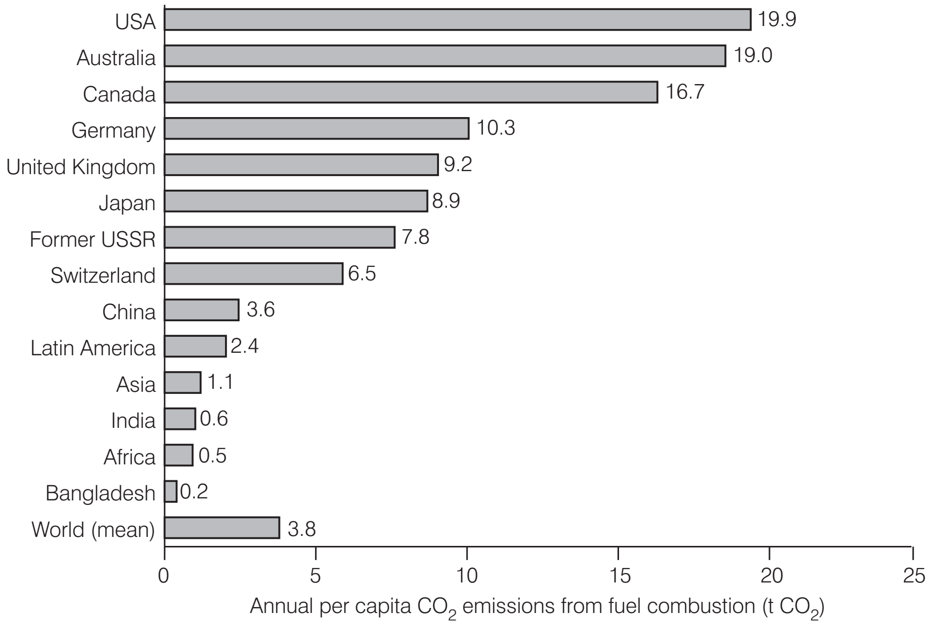
These contributions vary regionally. In developing countries, the burning of rain forests and agriculture have the highest climatic influence, while in industrial countries, the use of fossil fuels dominates. As indicated in Figure 1.7, the energy demand and resulting carbon dioxide emissions also vary enormously.

Per capita, the UK emits about 9 times more carbon dioxide than does India; for Germany it is 11 times more and for the US, 20 times more. If the people of all countries caused the same amount of anthropogenic carbon dioxide as those in the US, global carbon dioxide emissions would increase five times and the anthropogenic greenhouse effect would double. The per capita $CO_2$ emissions of road traffic alone in Germany are twice as high as the total per capita emissions in India. In the US the picture is even worse.

The reasons for climate change are controversial. Even today, studies are published questioning the anthropogenic greenhouse effect. In fact, part of the global temperature increase of 0.6°C during the past 100 years is linked to natural fluctuations. However, the majority comes from anthropogenic emissions. In most cases it is obvious that the authors who refute the existence of anthropogenic climate change are associated with lobby groups that would be disadvantaged if a radical change of energy policy were to take place.

There are several undeniable facts substantiating a creeping climate change. In 2001, the following events were seen as indications for the increasing greenhouse effect (IPCC, 2001):

- Worldwide, 1998 was the warmest year since temperature measurements began in 1861
- The 1990s were the warmest decade since records began
- Global snow cover and the extent of ice caps has decreased by 10 per cent since the late 1960s
- Non-polar glaciers are undergoing widespread retreat
- Global mean sea level rose by 0.1–0.2 m during the 20th century
- During the 20th century, precipitation increased by 0.5–1 per cent per decade




*Source:* IEA, 2003a

**Figure 1.7** *Annual per capita Carbon Dioxide Emissions from Fuel Combustion for Different Countries in 2001*

- Heavy precipitation events increased at mid latitudes and far northern latitudes
- The frequency and intensity of droughts in Asia and Africa increased in recent decades.

A detailed prediction of the consequences of the anthropogenic greenhouse effect is not possible. Climatic models can only give an estimate of what will happen should the emission of greenhouse gases continue unchecked.

If we do not reduce anthropogenic greenhouse gas emissions, the carbon dioxide concentration in the atmosphere will more than double by the end of this century with respect to pre-industrial values. As a result, the mean global temperature will rise more than 2°C. The currently predicted range is from +1.4°C to +5.8°C. Such a temperature rise is similar to that between the ice age of 18,000 years ago and today's warm period. However, the transition from the last ice age to the current warm period took over 5000 years, but we are discussing a temperature change that will happen over 100 years.

A temperature rise of +2°C or more than +0.1°C per decade is already a very critical value, which will cause catastrophic consequences for food production and ecosystems. Global warming will have a drastic influence on global forest viability and agriculture. Globally, the lack of food in some regions will get significantly worse due to a predicted widespread decrease in agricultural production. The result could be famines and mass migrations. Furthermore, global warming will increase storm intensities with disastrous effects in tropical regions as well as in mid-range latitudes. Global sea level will rise between 0.1 and 0.9 metres in this century. The long-term sea-level rise could be as high as several metres, with severe influences on low-lying regions. Recent flood disasters give us an indication of what is to come. For example, about 139,000 people died from floods in Bangladesh in 1991. Many low-lying regions and islands will disappear from the map.

It is a sad fact that these consequences cannot be avoided completely. The limiting of global warming to +2°C is possible only if enormous efforts are undertaken immediately. By the year 2100, the various greenhouse gas levels must be reduced drastically compared with 1990 levels. This could be achieved in the following way:

- decrease global carbon dioxide emissions by 70 per cent
- reduce global $N_2O$ and $CH_4$ emissions by 50 per cent and 5 per cent, respectively
- completely ban the use of all CFCs, halons and HFC-22.

Furthermore, demographers predict an increase of the world population to 15 billion (IPCC, 2000) (see also Table 1.16), more than twice the current population. Consequently, to achieve a 70 per cent reduction in global carbon dioxide emissions, the per capita carbon dioxide emissions in 2100 will have to be reduced to 15 per cent of the emissions for 1990.

The industrial countries cause the largest amount of emissions. The developing countries are currently lagging behind, but if they catch up, the industrial countries will have to achieve the following higher emission reductions for effective climate protection:

- 25 per cent reduction of $CO_2$ emissions by 2005 compared with 1990
- 50 per cent reduction of $CO_2$ emissions by 2020 compared with 1990
- 80 per cent reduction of $CO_2$ emissions by 2050 compared with 1990
- 90 per cent reduction of $CO_2$ emissions by 2100 compared with 1990.

This would mean a virtually complete withdrawal from the use of fossil fuels in this century. Technically and economically this is possible; however, in the face of a half-hearted climate policy, every possible effort has to be made.

It is not impossible to adhere to these climate reduction targets while still increasing global prosperity. However, everybody has to recognize the necessity of strong reductions and the consequences of failure. Sufficient possibilities to cover our energy demand without fossil energy sources exist today: the power industry could be based entirely on renewable energies. Thus, the question of *whether* our energy supply could be managed without fossil fuels is easy to answer. The question yet to be answered is: when will society be ready to establish a sustainable energy supply without fossil fuels and face up to its responsibilities to future generations?

# Nuclear Power versus the Greenhouse Effect

## Nuclear fission

Since the use of fossil fuels has to be reduced significantly within the coming decades, zero-carbon energy sources are required. One option is nuclear power. Here, we distinguish between nuclear fusion and nuclear fission.

All operational nuclear power stations utilize nuclear fission for electricity generation. Here, neutrons bombard the uranium isotope $^{235}$U and cause the fission of the uranium. Among others, krypton $^{90}$Kr and barium $^{143}$Ba are fission by-products. Furthermore, this fission reaction generates new free neutrons $^{1}$n that can initiate further fission reactions. The mass of the atomic particles after the fission is reduced compared to the original uranium atom. This so-called mass defect is converted to energy $\Delta E$ in the form of heat. The following nuclear reaction equation describes the fission process:

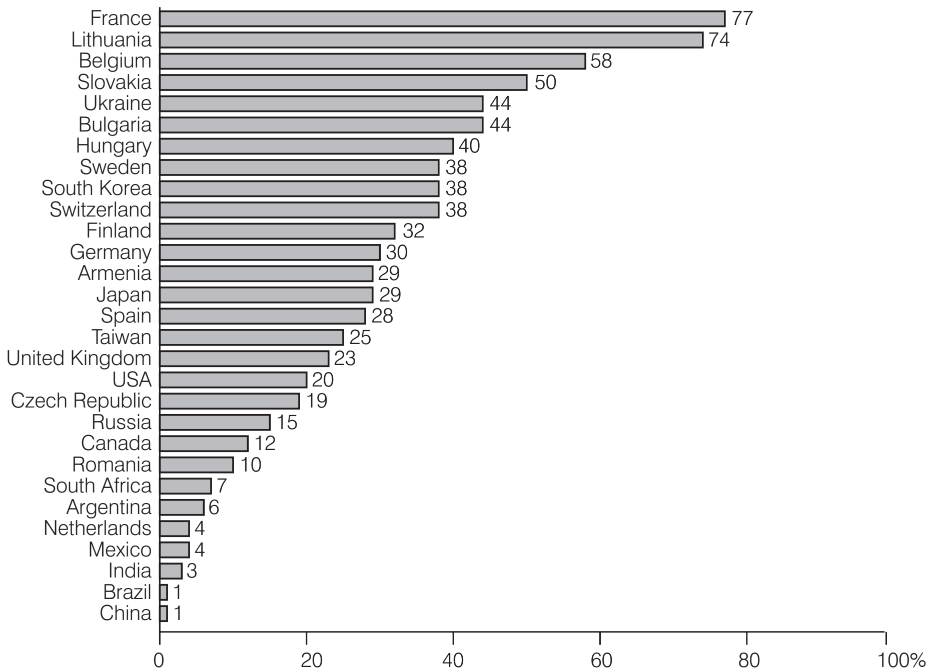
$$^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \longrightarrow {}^{90}_{36}\mathrm{Kr} + {}^{143}_{56}\mathrm{Ba} + 3\,{}^{1}_{0}\mathrm{n} + \Delta E \tag{1.4}$$

Since nature does not provide uranium in the form that is needed for technical utilization, it must be extracted from uranium ore. Rock with a uranium oxide content of more than 0.1 per cent is a workable uranium ore. Uranium mining produces huge amounts of waste that contains, in addition to some non-toxic components, a lot of radioactive residues. Uranium oxide from uranium ore contains only 0.7 per cent uranium-235. The largest portion is uranium-238, which is not usable for nuclear fission. Therefore, processing plants must enrich the uranium, i.e. the uranium-235 concentration must be increased to 2–3 per cent. In 2002, worldwide uranium production was about 34,000 metric tonnes.

Altogether, 428 nuclear power stations were in operation at the beginning of 2003, with an overall capacity of 353,505 MW. The average nuclear power station power was about 825 MW. Currently, nuclear power's share of the global primary energy demand is below 10 per cent. Figure 1.8 shows that nuclear power has a different contribution to electricity supply in different countries.

Nuclear power dominates the French electricity supply, whereas industrial nations such as Australia, Austria, Denmark, Norway or Portugal do not operate any nuclear power stations at all. Italy decided to abort nuclear power utilization after the Chernobyl disaster; Austria's decision pre-dated it. However, an electricity industry without nuclear power does not necessarily mean higher carbon dioxide emissions. For instance, hydro-electricity produces nearly 100 per cent of Norway's electricity. Iceland's electricity supply is nearly carbon dioxide free as a result of hydro and geothermal power.

If all fossil energy sources used today were replaced by nuclear power, about 10,000 new nuclear power stations would have to be built worldwide. The lifetime of a nuclear reactor is about 30 years, thus all these power stations




*Source:* DOE, 2003

**Figure 1.8** *Nuclear Power's Share of Electricity Generation in 2000*

would have to be renewed after this time. Therefore, a new power plant would have to go on-line every day. In this scenario, politically unstable nations would also acquire, as an unwanted side effect, access to nuclear technology. This would increase the risk of nuclear accidents, sabotage or military use of nuclear energy, resulting in unforeseeable associated costs which make this option increasingly expensive.

As described above, Earth has limited uranium reserves. If the majority of fossil energy sources were to be replaced by nuclear power, the uranium reserves would be depleted in a short time, depending on the nuclear technology employed. Therefore, nuclear fission can only be an alternative to fossil fuels in the medium term.

Nuclear fission does not emit any carbon dioxide directly, but the building of the power plant, uranium mining, transport and disposal result in the emission of significant amounts of carbon dioxide. These indirect carbon dioxide emissions are much lower than those associated with the operation of a coal-fired power plant but higher than the indirect carbon dioxide emission of, for example, wind turbines.

Transport and storage of radioactive materials bear further risks: uranium and fuel rods must be transported to different processing plants and power stations, and radioactive waste must be transported for further treatment and to intermediate and final storage sites. Toxic and highly radioactive waste such as spent fuel rods is already produced during normal operation of a nuclear power station. Besides other radioactive substances, they also contain about 1 per cent plutonium. One microgram of plutonium, i.e. one millionth part of a gram, is considered to be lethal when breathed in; it will cause death by lung cancer. Hence, one gram of plutonium could theoretically wipe out a whole city. There is no absolute safety guarantee with such nuclear material; the possibility of transport accidents and the emission of radioactive material is very real. Final storage of radioactive waste is also very problematic, because this waste will retain its lethal properties over thousands of years.

The normal operation of nuclear power plants also bears risks. Nuclear power stations continuously emit a very small amount of radioactivity. An increased rate of leukaemia in children living near a nuclear power plant has been reported. However, accepted scientific correlations do not exist at present.

The highest risk of nuclear fission is an MCA (maximum credible accident) in a power station. Such an accident would affect millions of people and the emitted radioactivity would make large regions uninhabitable. Many humans and animals would die from radiation or fall ill with cancer. An MCA can never be totally excluded. Nuclear accidents in Harrisburg and Chernobyl have made this clear. In recent years the risk of terrorist attacks has also increased the risk of an MCA.

The first big reactor accident happened on 28 March 1979 at Three Mile Island near Harrisburg, the capital of the US state of Pennsylvania. Large amounts of radioactivity escaped. Numerous animals and plants were harmed and the number of human stillbirths in the neighbourhood of the power plant increased after the accident and cancer rates increased drastically.

On 26 April 1986, another severe nuclear reactor accident happened in the city of Chernobyl in the Ukraine, which had about 30,000 inhabitants. The escaped radioactivity not only affected the vicinity of the plant but also affected Central Europe. Many workers who tried to stop further damage at the plant paid for their efforts with their lives. The number of stillbirths and the incidence of cancer due to exposure to radiation increased significantly in the following years.

As has already been noted, civilian use of nuclear power stations is not their only potential use; they can also be used for military applications. This is one reason why civilian nuclear power has been promoted in some countries. The use of nuclear power in politically unstable countries can provoke international crises. Countries such as Iran, Iraq and North Korea have promoted nuclear power, probably also to exploit its military potential. If the use of civilian nuclear power is encouraged, the risk of nuclear crises and the risk that terrorists will come into possession of nuclear material will rise significantly.

The number of incalculable risks is balanced by the undisputed benefits of civilian use of nuclear power. Other cleaner technologies than nuclear power exist and the potentially enormous costs associated with nuclear accidents suggest that the insistence on withdrawal from the nuclear programme is perfectly justified.

### Nuclear fusion

The hope of many scientists and politicians is pinned on a totally new nuclear technology: nuclear fusion. Already many billions of Euros have been spent in order to develop this technology. The model for this technology is the sun, which produces its energy by fusing hydrogen nuclei; the aim is to copy this process on Earth. Deuterium $^{2}D$ and tritium $^{3}T$ are fused to Helium $^{4}He$. This reaction generates one neutron $^{1}n$ and energy $\Delta E$. The equation of this reaction is:

$$ {}^{2}_{1}\mathrm{D} + {}^{3}_{1}\mathrm{T} \longrightarrow {}^{4}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n} + \Delta E \tag{1.5} $$

To instigate this reaction the particles must be heated to temperatures over one million degrees Celsius. Since no known material can survive these high temperatures, technologies such as locking the reaction materials into intense magnetic fields are examined.

Deuterium and tritium for nuclear fusion exist in abundance on Earth, so this technology will not be limited by the availability of the raw materials. However, the question whether this technology will ever work cannot be answered today. Some critics say that the only thing that never changes for nuclear fusion is the remaining time needed for the development of a working reactor, which has been estimated to be 50 years for the past 50 years.

Even if this technology will work eventually, there are good reasons against spending more money on this technology. On the one hand, nuclear fusion will be much more expensive that today's nuclear fission. Renewable energies will certainly be much more economical in 50 years than nuclear fusion. On the other hand, the operation of a nuclear fusion plant also produces radioactive materials that bear risks although the risk of an MCA does not exist for a nuclear fusion plant. For the development of nuclear fusion, large amounts of money have been spent that could have been used to develop other sustainable technologies. The last and most important reason is the long time that is still needed to bring this technology to maturity. To stop global warming today, working alternatives to our present energy supply are needed urgently. Therefore, to wait for a nuclear fusion reactor that might or might not work at some time in the distant future is not the answer.

## Renewable Energies

Even if the use of fossil fuels can be reduced significantly, and accepting that nuclear power is no long-term alternative, the question remains as to how the future supply of energy can be secured. The first step is to significantly increase the efficiency of energy usage, i.e. useful energy must be produced from a much smaller amount of primary energy, thus reducing carbon dioxide emissions.

The increasing global population and the unsatisfied demand of the developing countries will more than cancel out possible reductions due to higher energy efficiency. This problem is very well described in the book *Factor Four* by Weizsäcker and Lovins:

> *In the next 50 years, twice the current global prosperity must be achieved with half the energy and demand on natural resources* (Weizsäcker et al, 1998).

Renewable energies will be the key to this development, because they are the only option that can cover the energy demand of Earth in a climatically sustainable way.

*Renewable energy sources* are energy resources that are inexhaustible within the time horizon of humanity. Renewable types of energy can be subdivided into three areas: solar energy, planetary energy and geothermal energy. The respective available annual energy globally is:

- solar energy 3,900,000,000 PJ/year
- planetary energy (gravitation) 94,000 PJ/year
- geothermal energy 996,000 PJ/year

Energy stored in wind or rain, which also can be technically exploited, originate from natural energy conversions. The annual renewable energy supply exceeds the global energy demand shown in the previous section on evolution of world energy demand by several orders of magnitude. Renewable energies can, theoretically, cover the global energy demand without any problem. However, that does not mean that the transition from our present energy supply to renewable energy supplies will be possible without any problems. On the contrary, renewable energy supplies need a totally different infrastructure compared to what has been created during the past decades.

The present energy supply depends mainly on fossil energy resources. The priority is to produce and transport fossil fuels in the most economical fashion and to convert them cheaply into other types of energy in central power stations. The main advantage of fossil fuel-based energies is their ready availability. Fossil energy can be used whenever there is consumer demand.

In contrast to fossil fuels, the availability of most renewable energy sources fluctuates. A fully renewable energy supply must not only convert renewable energy sources into useful energy types, such as electricity or heat, but must also guarantee their availability. This can be done through large energy storage systems, global energy transport or adaptation of the demand to the available energy. It is not in question that renewable energies can cover our energy demand; the open questions are what share the different renewable energy sources will require for an optimal mix and when will they provide the entire energy demand. In terms of global warming, the transformation of our energy supply is the single most important challenge of the 21st century.

## Geothermal energy

Geothermics utilizes the heat of Earth's interior. Geothermal power stations can utilize geothermal heat and convert it into electricity or feed it into district heating systems. In the Earth's interior, temperatures are somewhere between 3000°C and 10,000°C. Radioactive decay releases enough energy to produce such temperatures. The heat flow in the Earth's crust is relatively low and increases with depth. Volcanic eruptions demonstrate the enormous activity in the Earth's interior. The option of geothermics is demonstrated persuasively in Iceland and the Philippines, where it provides more than 20 per cent of the electricity supply.

The temperature differences between the Earth's interior and crust cause a continuous heat flow. The mean global value of this heat flow at the Earth's surface is 0.063 W/m$^2$. The total energy flow is of the same magnitude as the world's primary energy consumption. Applying the constraint that the upper strata of the Earth's crust should not be cooled down significantly and that the technical effort required must not be prohibitively high, only a portion of the available geothermal energy is usable. Today geothermal energy is only exploited in regions with geothermal anomalies. These regions record high temperatures at low depths.

Only very few regions exist with such high temperatures directly under the Earth's surface. Geysers can indicate such places. Geothermal heat pumps do not require high temperature differentials, although such differentials do help to make them more economical. Electrically driven compression heat pumps can be used to boost temperature differentials and these have reached technical maturity. However, the ecological benefits of heat pumps driven with electrical energy produced by power plants burning fossil fuels are low. On the other hand, if renewable sources provide the power required to drive the heat pump, the system becomes one avenue for providing a zero-carbon heating system. These systems are rarely used today.

Another technique that uses geothermal energy from hot, dry rocks at great depths is the so-called hot dry rock method (HDR). First a cavity is drilled into hot rocks (300°C) at a depth between 1000 and 10,000 m. Pressurized cold water is pumped into the cavity, heated up, and transported to the surface where a steam power plant generates electricity. This technology is still experimental.

## Planetary energy

The different celestial bodies, in particular our moon, exchange mutual forces with Earth. The motion of the celestial bodies results in continuously varying forces at any specific point on the Earth's surface. The tides are the most obvious indicator of these forces. The movement of enormous water masses in the oceans creating the tides involves enormous amounts of energy.

Tidal energy can be used by power plants on coasts with high tidal ranges. At high tide, water is let into reservoirs and is prevented from flowing back as the tide ebbs, creating a potential difference between the collected water and water outside the reservoir. The collected water is then released though turbines into the sea at low tide. The turbines drive electric generators to produce electricity. Today there are only a few tidal power plants in operation.

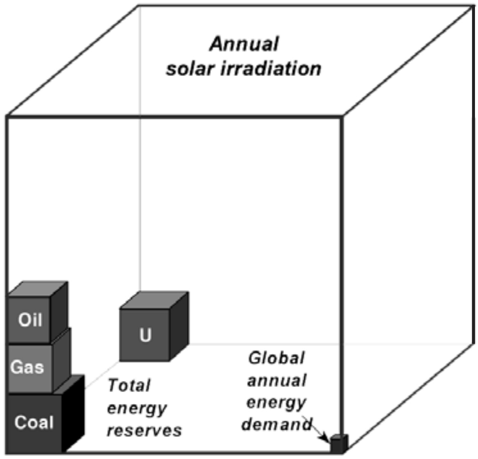



**Figure 1.9** *Energy Cubes: the Annual Solar Irradiation Exceeds Several Times the Total Global Energy Demand and All Fossil Energy Reserves*

The largest tidal power plant, with a capacity of 240 MW, is situated at the Rance estuary in France. However, tidal power plants always have large impacts on nature. The amount of power that can be theoretically produced by tidal power plants globally is relatively low.

## Solar energy

By far the largest energy resource is the sun. Annually, $3.9 \cdot 10^{24}$ J = $1.08 \cdot 10^{18}$ kWh of solar energy reaches the surface of the Earth. This is about ten thousand times more than the annual global primary energy demand and much more than all available energy reserves on earth. In other words, using one-ten-thousandth part of the incoming sunlight would cover the whole energy demand of mankind. Figure 1.9 illustrates these values with energy cubes.

There is a distinction between direct and indirect solar energy. Technical systems using direct solar energy convert incoming solar radiation directly into useful energy, for instance electricity or heat. Wind, river water and plant growth are indirect forms of solar energy. Here, natural processes convert solar energy into other types of energy. Technical systems can use these indirect types of solar energy as well.

The theoretical foundations of solar radiation needed for all technical solar systems are reviewed in Chapter 2. The following sections briefly describe the different technologies using direct and indirect solar energy. Some of them are described in more detail in the following chapters.

### Use of direct solar energy

The following technologies can utilize direct solar energy:

- solar thermal power plants
- photolysis systems for fuel production
- solar collectors for water heating
- passive solar heating systems
- photovoltaics, solar cells for electricity generation.

*Solar thermal power plants* Solar thermal power (power derived from the thermal use of solar energy) can be used to generate electricity or to produce high-temperature steam. Solar thermal power plants used for electricity generation are:

- parabolic trough power plants
- solar thermal tower power plants
- solar furnace
- Dish–Stirling systems
- solar chimney power plants.

*Parabolic trough power plants* were the first type of solar thermal power plant technologies operating commercially. Nine large power plants called SEGS I to IX (Solar Electric Generation System) were commissioned in California between 1984 and 1991. These power plants have a nominal capacity of between 13.8 and 80 MW each, producing 354 MW in total.

The parabolic trough collector consists of large curved mirrors, which concentrate the sunlight by a factor of 80 or more to a focal line. A series of parallel collectors are lined up in rows 300–600 metres long. Multiple parallel rows form the solar collector field. The collectors moved on one axis in order to follow the movement of the sun; this is called tracking. A collector field can also be formed by long rows of parallel Fresnel collectors. In the focal line of the collectors is a metal absorber tube, which usually is embedded into an evacuated glass tube to reduce heat losses. A special selective coating that withstands high temperatures reduces radiation heat losses.

In the Californian systems, thermo oil flows through the absorber tubes. These tubes heat the oil to 400°C. A heat exchanger transfers the thermal energy from the oil to a water–steam cycle (also called the Rankine cycle). A pump pressurizes the water and an economizer, vaporizer and a superheater jointly produce superheated steam. This steam expands in a two-stage turbine; between the high- and low-pressure parts of this turbine is a reheater. The turbine itself drives an electrical generator that converts the mechanical energy into electrical energy; the condenser after the turbine condenses the steam back to water, which allows the closing of the cycle by feeding this water back into the initial pump.

Solar collectors can also produce superheated steam directly. This makes the thermo oil superfluous and reduces costs due to savings associated with not using the expensive thermo oil. Furthermore, heat exchangers are no longer needed. However, direct solar steam generation is still at the prototype stage.

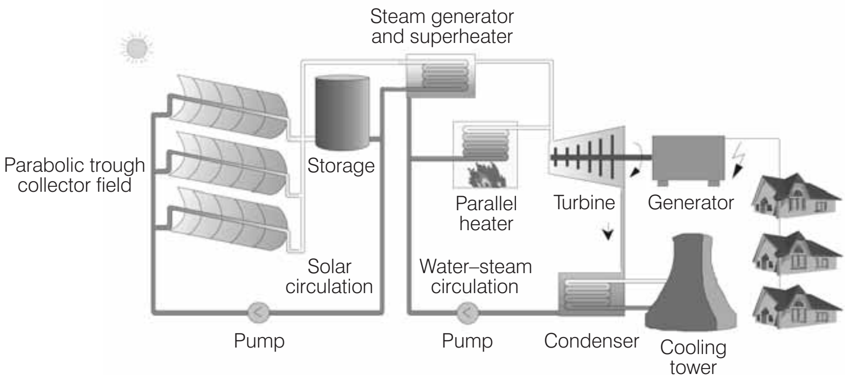



**Figure 1.10** *Principle of a Parabolic Trough Solar Power Plant*

One important advantage of solar thermal power plants is that they can operate with other means of water heating and thus a hybrid system can ensure security of supply. During periods of insufficient irradiance, a parallel burner can be used to produce steam. Climate-compatible fuels such as biomass or hydrogen produced by renewable energy can also fire this parallel burner. Figure 1.10 shows the principle of a parabolic trough solar power plant.

In *solar thermal tower power plants*, hundreds, or even thousands, of large two-axis tracked mirrors are installed around a tower (Figure 1.11). These slightly curved mirrors are called heliostats. A computer is used to calculate the ideal position for each of these and positioning motors ensure precise focus on the top of the tower. The absorber is located at the focus of the mirrors on top of the tower. The absorber will be heated to temperatures of typically 1000°C or more. Hot air or molten salt transports the heat from the absorber to a steam generator where superheated steam is produced. This steam drives a turbine and an electrical generator as described above for the trough power plants. Demonstration plants exist in the US, Spain and Israel. Commercial power plants are under construction in Spain.

**Figure 1.11** *Demonstration Solar Thermal Tower Power Plant in Spain*

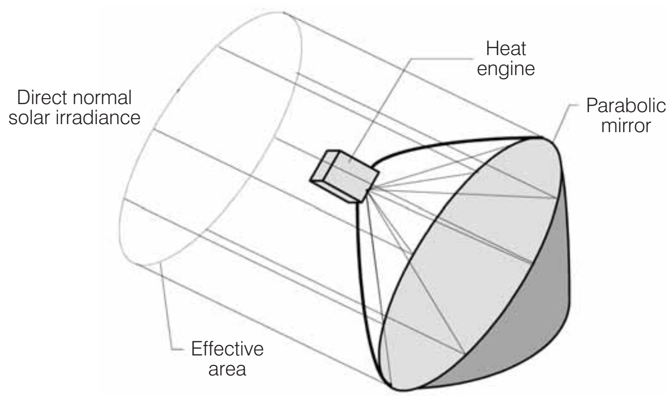



**Figure 1.12** *Principle of a Dish–Stirling System*

Another system using mirrors is the solar furnace. The solar furnace in Odeillo (France) consists of various heliostat mirrors that have been set up on sloping ground. These heliostats reflect the sunlight onto a concave mirror with a diameter of 54 m. At the focus of this mirror, temperatures up to 4000°C can be reached and used for scientific experiments or, in a commercial product, for industrial processes. Further solar furnaces exist in Almería (Spain) and Cologne (Germany).

So-called Dish–Stirling systems can be used to generate electricity in the kilowatt range. A parabolic concave mirror (the dish) concentrates sunlight. A two-axis tracked mirror tracks the sun with the required high degree of accuracy. This is necessary in order to achieve high efficiencies. The receiver at the focus is heated to 650°C. The heat absorbed drives a Stirling motor, which converts the thermal energy into mechanical energy that is used to drive a generator producing electricity. If sufficient sunlight is not available, combustion heat from either fossil fuels or bio-fuels can also drive the Stirling engine and generate electricity. The system efficiency of Dish–Stirling systems can reach 20 per cent or more. Some Dish–Stirling system prototypes have been tested successfully in a number of countries; however, the cost of electricity generation using these systems is much higher than that of trough or tower power plants. Large-scale production might achieve significant cost reductions for Dish–Stirling systems. Figure 1.12 shows the principle of a Dish–Stirling system.

A *solar chimney power plant* has a high chimney (tower), with a height of up to 1000 metres. This is surrounded by a large collector roof, up to 5000 metres in diameter, that consists of glass or clear plastic supported on a framework. Towards its centre, the roof curves upwards to join the chimney, creating a funnel. The sun heats up the ground and the air under the collector roof, and the hot air follows the upward slope of the roof until it reaches the chimney. There, it flows at high speed through the chimney and drives wind generators at the bottom. The ground under the collector roof acts as thermal storage and can even heat up the air for a significant time after sunset. The

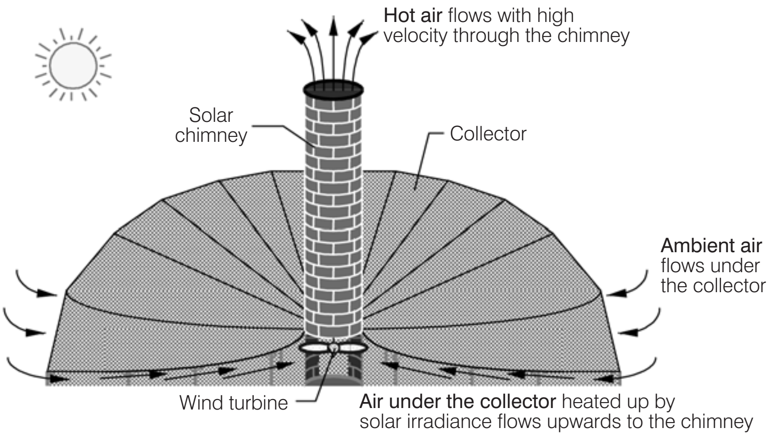



**Figure 1.13** *Principle of the Solar Chimney Power Plant*

best efficiency of solar chimney power plants is currently below 2 per cent. It depends mainly on the height of the tower. Due to the large area required, these power plants can only be constructed on cheap or free land. Suitable areas could be situated in desert regions. However, the whole power plant has additional benefits, as the outer area under the collector roof can also be utilized as a greenhouse for agricultural purposes. As with trough and tower plants, the minimum economic size of a solar chimney power plant is in the multi-megawatt range. Figure 1.13 illustrates the principle of the solar chimney power plant.

Solar thermal power plants typically have poor part-load behaviour and should be installed in regions with a minimum of around 2000 full-load hours in Earth's sunbelt. However, thermal storage can increase the number of full-load hours significantly. The specific system costs are between €2000/kW and €5000/kW depending on the system size, system concept and storage size. Hence, a 50-MW solar thermal power plant will cost €100–250 million. At good sites, today's solar thermal power plants can generate electricity at around €0.15/kWh. Series production could soon bring down these costs to below €0.10/kWh. The potential for solar thermal power plants is enormous: for instance, about 1 per cent of the area of the Sahara desert covered with solar thermal power plants would theoretically be sufficient to meet the entire global electricity demand. Therefore, it is highly probable, as well as desirable, that solar thermal power systems will play an important role in the world's future electricity supply.

*Solar collectors for water heating* Solar thermal energy can not only be used for the production of high-temperature heat and electricity but also for covering the demand for low-temperature heat for room heating or domestic water heating. Solar collector systems are currently used mainly for domestic water heating and swimming pool heating, but they have rarely been used for room heating systems until now.

China is by far the world's largest solar water heater manufacturer and user (see also the section on 'Use of renewable energy sources for heat and fuel protection'). By the end of 2002 the accumulated installed area of solar domestic hot water systems in China was about 40 million $m^2$. The annual production and sales volume was expected to reach about 8 million $m^2$ in 2002. There are more than one thousand manufacturers producing and selling solar thermal systems, realizing a total turnover of more than one billion Euros. Evacuated tube collectors dominate the Chinese market and exports. In Europe about 1.1 million $m^2$ had been installed by 2002. Here the flat-plate collector dominates. About half the new installations have been realized in Germany. Chapter 3 describes solar collectors for domestic water heating in detail.

Besides collector systems that use solar energy actively, so-called *passive* use of solar energy is possible. Well-oriented buildings with intelligently designed glass facades or transparent insulation are used for this purpose. With the combination of active and passive use of solar energy, it is also possible to build zero-energy houses, especially in moderate climatic zones such as Central Europe. The entire energy demand of these buildings is covered by solar energy. Some prototypes, for instance the energy self-sufficient solar house in Freiburg (Germany), have proven the high potential of solar energy use (Voss et al, 1995).

*Photovoltaics* Another technology for using solar energy to generate electricity is photovoltaics. Solar cells convert the sunlight directly into electrical energy. The potential for photovoltaic systems is huge. Even in countries with relatively low annual solar irradiance such as Germany, photovoltaics theoretically could provide more than the total electricity demand. However, an electricity supply based entirely on photovoltaic systems is not feasible since it would generate a high surplus of energy in the summer that would have to be stored at considerable cost. The combination of photovoltaic systems with other renewable energy generators such as wind power, hydro power or biomass is preferable. This would allow the whole electricity demand to be satisfied free of carbon dioxide emissions while avoiding high storage capacities and cost (Quaschning, 2001). Chapter 4 deals with photovoltaics in detail.

### Indirect use of solar energy

Natural processes transform solar energy into other types of energy. Technical energy converters can utilize these indirect solar energy sources. One example for indirect types of solar energy is waterpower. Solar irradiation evaporates water from the oceans. This water rains down at higher altitudes. Streams and rivers collect this water and close the cycle at the estuaries. Hydro-electric power stations can convert the stored kinetic and potential energy of the water into electricity. Types of indirect solar energy are:

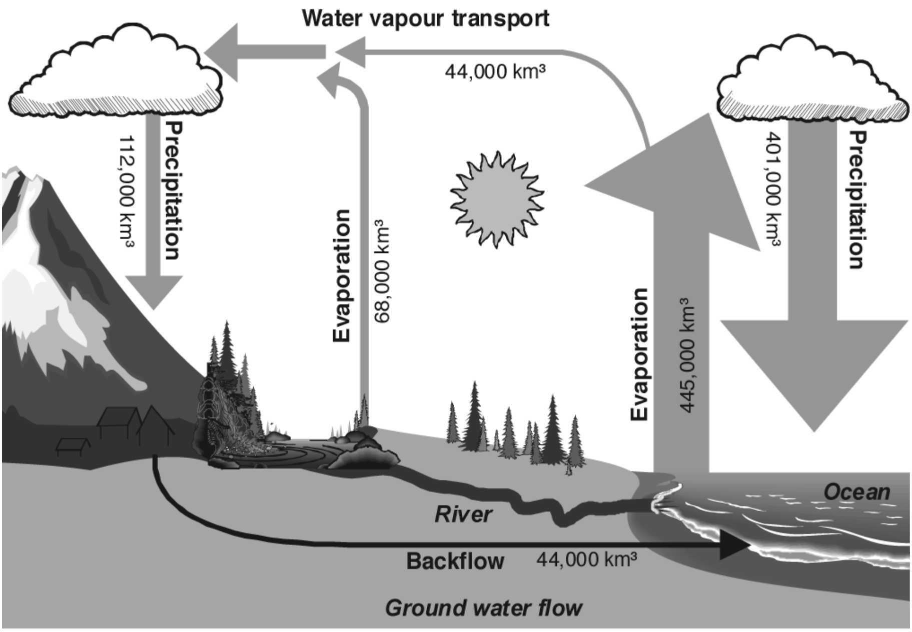



**Figure 1.14** *Principle of the Global Water Cycle*

- evaporation, precipitation, water flow
- melting of snow
- wave movements
- ocean currents
- biomass production
- heating of Earth's surface and the atmosphere
- wind.

*Hydro-electric power* The sun evaporates every year on average 980 litres of water from every square metre of the Earth's surface, in total 500,000 km$^3$ (see Figure 1.14). About 22 per cent of the solar radiation energy reaching Earth is needed to drive this water cycle. Nearly 20 per cent of the evaporated water rains down on landmasses, where the majority evaporates again. About 40,000 km$^3$ flows back to the oceans in rivers or groundwater. This is equal to more than one billion litres per second. Technically, the energy of this flow can be used.

About 160 EJ is stored in rivers and seas, which is equivalent to roughly 40 per cent of the global energy demand. About one-quarter of that energy could be technically exploited, so that nearly 10 per cent of the global energy demand could be provided free of carbon dioxide emissions by hydro-electric power. The potential for hydro-electric power in Europe is already relatively well exploited, whereas large unexploited potentials still exist in other regions of the world.

The history of using hydro power reaches back many centuries. Initially, watermills were used to convert hydro power into mechanical energy.

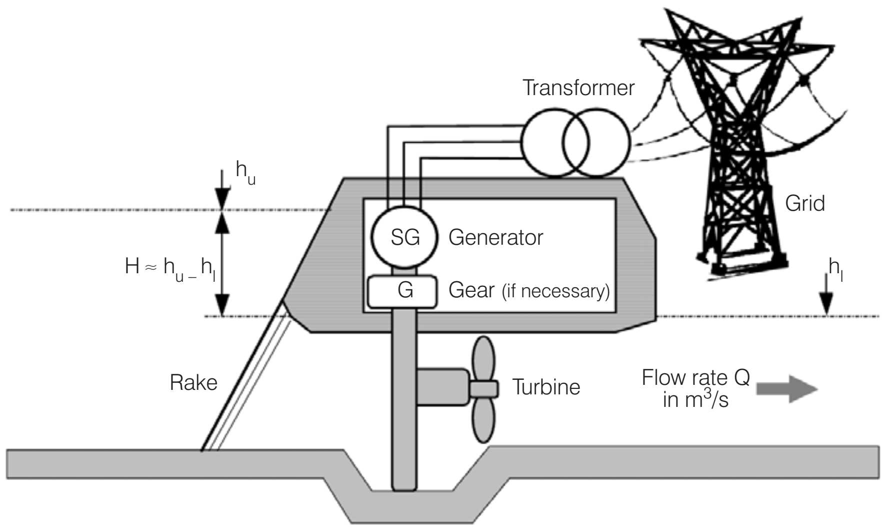



**Figure 1.15** *Principle of a Hydro-electric Power Plant*

Electricity generation from hydro power started at the end of the 19th century and has achieved technical sophistication. A weir creates a height (or 'potential') difference (also called a 'head') between the water before and after the weir (see Figure 1.15). This potential difference can be utilized by a power plant. The water flows through a turbine, which transforms the potential energy into mechanical energy. An electric generator converts this into electricity. Depending on the head height and flow rate, different turbines are used. Common turbines are the Pelton, Francis or Kaplan turbines. Finally, a transformer converts the generator voltage to the grid voltage.

The power output:

$$P = \eta_G \cdot \eta_T \cdot \rho_W \cdot g \cdot Q \cdot H \tag{1.6}$$

of the power plant can be calculated from the efficiency of the generator $\eta_G$ and the turbine $\eta_T$, the density $\rho_W$ of the water ($\rho_W \approx 1000$ kg/m$^3$), the head $H$ (in m), the gravitation constant $g$ ($g = 9.81$ m/s$^2$) and the flow rate $Q$ (in m$^3$/s).

**Table 1.8** *Contribution of Hydro-electricity to the Net Electricity Generation in Different Countries*

| *Country* | *Paraguay* | *Norway* | *Brazil* | *Iceland* | *Venezuela* | *Austria* | *Canada* |
|---|---|---|---|---|---|---|---|
| Share (%) | 100 | 99 | 89 | 83 | 75 | 71 | 60 |
| *Country* | *Russia* | *China* | *Australia* | *US* | *Germany* | *UK* | *Netherlands* |
| Share (%) | 19 | 17 | 8 | 7 | 4 | 1.4 | 0.1 |

*Source:* DOE, 2003

*Note:* Left: Upper Reservoir; Right: Lower Reservoir, Penstock and Surge Shaft

**Figure 1.16** *Pumped-storage Hydro-electric Power Plant in Southern Spain near Malaga*

In addition to electricity generation in river or mountain power plants there are so-called pumped-storage hydro-electric power plants (see Figure 1.16). These power plants can be used for electricity storage. In times of excess power generation, a pump transports water in a storage basin to a higher level. When the water flows back, a turbine and a generator can convert the potential energy of the water back into electricity.

Hydro-electric power is, apart from the use of biomass, the only renewable energy resource that covers a noticeable proportion of the global energy demand. The resources and the contribution of hydro-electricity to the electricity supply vary from country to country as shown in Table 1.8.

The Itaipu hydro-electric power plant shown in Figure 1.17 is situated in the border area between Brazil and Paraguay. It is at present the largest hydro-electric power plant in the world. It has a rated capacity of 12.6 GW and generated 24.3 per cent of the electricity demand of Brazil and 93.6 per cent of that of Paraguay in the year 2000. The total electricity generation in the same year was 93.4 billion kWh. Table 1.9 shows the enormous dimensions of the Itaipu power plant. However, an even larger plant is under construction: the

**Table 1.9** *Technical Data of the Itaipu Hydro-electric Power Plant*

| *Reservoir* | | *Dam* | | *Generator units* | |
|---|---|---|---|---|---|
| Surface | 1350 $km^2$ | Maximum height | 196 m | Number | 18 (9 each of 50 Hz and 60 Hz) |
| Extent | 170 km | Overall length | 7760 m | Rated power | 715 MW each |
| Volume | 29,000 $km^3$ | Concrete volume | 8.1 million $m^3$ | Weight | 3343/3242 t each |

*Source:* Itaipu Binacional (2003)

*Source:* Itaipu Binacional (2003)

**Figure 1.17** *Itaipu Hydro-electric Power Plant*

Three Gorges hydro-electric power plant in China will generate 18.2 GW when completed.

Such large hydro-electric power plants are not uncontroversial because they also have a negative impact on nature and local conditions. For the Three Gorges power plant in China, several hundred thousand people had to be relocated. An example of adverse environmental effects is the Aswan dam in Egypt. It stopped the Nile from flooding, and hence from replenishing the nutrients in the intensively farmed flood planes. The artificial irrigation required to make up for the missing fertilization caused salination of the ground and harvests deteriorated. The area around the estuary also is affected by increasing soil erosion.

Before planning large hydro-electric power plants, the advantages and disadvantages should be considered carefully. On the one hand, hydro-electric power is a technology that can generate electricity without carbon dioxide emission at very low cost. On the other hand, there are negative impacts as detailed above. Small hydro-electric power plants can be an alternative. Their negative impacts are usually much smaller, but their relative costs are much higher.

The tidal power plants described on p21 also utilize hydro power. Other types of power plants that use hydro power are wave or ocean current power plants. However, these power plants are still at the prototype stage at present.

*Biomass* Life on Earth is possible only because of solar energy, a substantial amount of which is utilized by plants. The following equation describes, in general, the production of biomass:

**Table 1.10** *Efficiencies for Biomass Production*

| | | | |
|---|---|---|---|
| Oceans | 0.07% | Woods | 0.55% |
| Fresh water | 0.50% | Maize | 3.2% |
| Man-made landscape | 0.30% | Sugarcane | 4.8% |
| Grassland | 0.30% | Sugar beet | 5.4% |

$$H_2O + CO_2 + \text{substances} + \Delta E \longrightarrow \underbrace{C_k H_m O_n}_{\text{Biomass}} + H_2O + O_2 + \begin{matrix}\text{metabolic}\\ \text{products}\end{matrix} \tag{1.7}$$

Dyes such as chlorophyll split water molecules $H_2O$ using the energy $\Delta E$ of the visible sunlight. The hydrogen H and the carbon dioxide $CO_2$ taken from the air form biomass $C_kH_mO_n$. Oxygen $O_2$ is emitted during that process. Biomass can be used for energy in various ways. Such use converts biomass back again to $CO_2$ and $H_2O$. However, this conversion emits as much $CO_2$ as the plant had absorbed from the atmosphere while it was growing. Biomass is a carbon dioxide-neutral renewable energy source as long as the resource is managed sustainably.

A comparison of biomass production with other energy conversion processes is based on the estimated efficiencies of various plants. This efficiency describes what percentage of solar energy is converted to biomass. The average efficiency of global biomass production is about 0.14 per cent.

Table 1.10 shows some specific efficiencies of different methods of biomass production. The efficiency is calculated based on the calorific values given in Table 1.11 of the biomass grown in a certain area over a given time, which is then divided by the solar energy incident in this area during the same period of time.

Biomass usage can be classified as use of organic waste or agricultural residues and the cultivation of purpose-grown energy plants. Biomass can be used, for instance, in combustion engines, typically combined heat and power (CHP) plants. These CHP plants are usually smaller than large conventional coal or gas power plants, because it is important to minimize biomass transportation distances. Therefore, these power plants usually have a capacity of a few MW. Figure 1.18 shows a power station that is fired with residues from olive oil production.

**Table 1.11** *Calorific Values of Various Biomass Fuels*

| *Fuel (anhydrous)* | *Lower calorific value (LCV)* | *Fuel (anhydrous)* | *LCV* |
|---|---|---|---|
| Straw (wheat) | 17.3 MJ/kg | China reed | 17.4 MJ/kg |
| Non-flowering plants (wheat) | 17.5 MJ/kg | Colza oil | 37.1 MJ/kg |
| | | Ethanol | 26.9 MJ/kg |
| Wood without bark | 18.5 MJ/kg | Methanol | 19.5 MJ/kg |
| Bark | 19.5 MJ/kg | Petrol (for comparison) | 43.5 MJ/kg |
| Wood with bark | 18.7 MJ/kg | | |