1

Energy and Electricity

1.1 The World Energy Scene

1.1.1 History

Energy demand in the pre-industrial world was provided mostly by man and animal power and to a limited extent from the burning of wood for heating, cooking and smelting of metals. The discovery of abundant coal, and the concurrent technological advances in its use, propelled the industrial revolution. Steam engines, mechanized production and improved transportation, all fuelled directly by coal, rapidly followed. The inter-war years saw the rise of oil exploration and use. Access to this critical fuel became a key issue during the Second World War. Post-war industrial expansion and prosperity was increasingly driven by oil, as was the massive growth in private car use. More recently a new phase of economic growth has been underpinned to a great extent by natural gas.

A substantial proportion of coal and gas production is used to generate electricity, which has been widely available now for over a century. Electricity is a premium form of energy due to its flexibility and ease of distribution. Demand worldwide is growing, driven by the explosion in consumer electronics, the associated industrial activity and the widening of access to consumers in the developing world.

1.1.2 World Energy Consumption

The present global yearly *primary energy*[1] consumption is, in round figures, about 500 EJ.[2] This is equivalent to about 1.4 x10^{17} Wh or 140 000 TWh . Dividing this figure by the number of hours in the year gives 16 TW or 16 000 GW as the average rate of world primary power

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[1] Primary energy is the gross energy before its transformation into other more useful forms like electricity.

[2] The unit of energy in the SI system is the joule, denoted by J. Multiples of joule are kJ, MJ, GJ, TJ (T for tera denoting 10^{12}) and EJ (E for Exa denoting 10^{18}); the unit of power is the Watt (W) and represents the rate of work in joules per second. Electrical energy is usually charged in watt-hours (Wh) or kWh. Joules can be converted into Wh through division by 3600.

Renewable Energy in Power Systems Leon Freris and David Infield

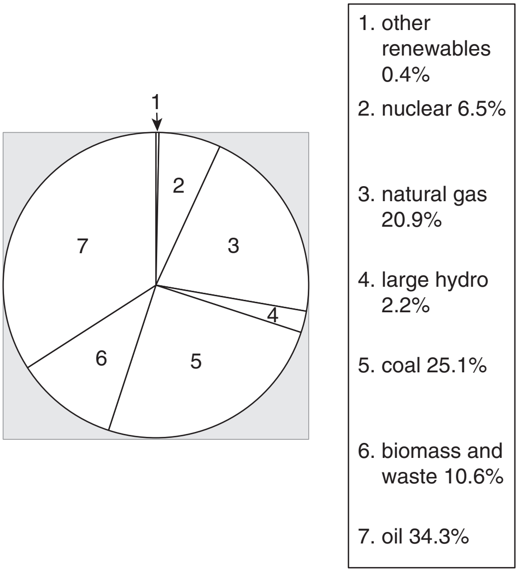

Figure 1.1 Percentage contribution to world primary energy

consumption. The pie chart in Figure 1.1 shows the percentage contribution to world primary energy from the different energy sources according to data taken from the International Energy Agency (IEA) Key World Energy Statistics, 2006.

The world demand for oil and gas is increasing significantly each year. The major part of this increase is currently taken up by India and China where industrialization and the demand for consumer products is escalating at an unprecedented pace. The world consumption in 2006 increased by more than twice Britain's total annual energy use and is the largest global yearly increase ever recorded. China alone accounted for roughly 40% of this increase. The IEA forecasts that by 2030 demand for energy will be some 60% more than it is now.

1.1.3 Finite Resources

It is extremely difficult to determine precise figures on the ultimate availability of fossil fuels. According to the major oil and gas companies, still significant new resources of oil are being developed, or remain to be discovered. A safe assessment is that there is enough oil from traditional sources to provide for the present demand for 30 years. The latest figures for global gas reserves indicate that these are approximately 50% higher than oil at some 60 years of current demand, and gas is far less explored than oil so there is probably more to be found. There are, however, unconventional hydrocarbon resources such as heavy oil and bitumen, oil shale, shale gas and coal bed methane – whose total global reserves have been assessed very roughly to be three times the size of conventional oil and gas resources. These are more expensive to extract but may become exploitable as the price of fossil fuels increases due to the steady depletion of the more easily accessible reserves. Fortunately for fossil fuel dependent economies, coal reserves are considered to be many times those of oil and gas and could last for hundreds of years. The downside of coal is its high carbon content, a topic to be discussed later.

Much debate is currently focused on when the so-called peak oil and gas might occur. This is when the oil and gas extraction rate starts to fall and occurs well before resources run out. It is important because it signals that demand will most likely not be fully met, with prices rising significantly as a consequence. Certainly the UK's North Sea reserves of oil and gas are fast declining with peak extraction having already occurred in 2003. Given the enormous investment in extraction and supply infrastructure, and the profits to be made, it would be surprising if those with vested interests did not work hard to maintain confidence in these sources.

Fuel for nuclear fission is not unlimited and several decades ago this has prompted interest in the fast breeder reactor which in effect extends the life of the fuel. However, the political dangers inherent in the fast breeder cycle, with its production of weapons grade plutonium, has limited its development to a few prototype reactors which had major operational problems and are now defunct. The lifetime of uranium reserves for conventional fission at current usage has been estimated by some as around 50 years, but such calculations are very dependent on assumptions. If an extremely high ore price is tolerable, then very low grades of uranium ore can be considered as possible reserves. The DTI cites OECD/NEA 'Red Book' figures to claim that based on 2004 generation levels, known uranium reserves (at $130/kg) will last for around 85 years (see References [1] and [2]).

1.1.4 Energy Security and Disparity of Use

Energy security is a major concern worldwide. A large part of the world's oil is located in the Middle East and other politically unstable countries. The conflict between 'Western' and 'Islamic' cultures is at present exacerbating the anxiety over reliability of energy supply. Russia is a major producer of gas but recent events in Ukraine have made European countries aware how dependent they are on this single source. The USA is the world's largest consumer of energy and is heavily dependent on imported oil. With economic growth seen as being intrinsically linked to cheap fuel it is difficult to imagine political parties, in the USA or elsewhere, proposing policies that require voters to drastically curtail their consumption and therefore alter their lifestyles.

Another disturbing aspect is the disparity in consumption between rich and poor countries: the richest billion people on the planet consume over 50% of all energy, while the poorest billion consume around 4%. This is an added source of tension and of accusations that the developed countries are profligate in the use of energy. To excuse this high consumption on grounds of high industrial activity is simply wrong. Japan, for example, is the world's second largest economy but has a per capita energy consumption half that of the US.

1.2 The Environmental Impact of Energy Use

1.2.1 The Problem

Fossil fuels have one thing in common: they all create carbon dioxide when burnt. They are a key part of the Earth's long term carbon cycle, having been laid down in geological periods when the climate was tropical across much of the planet and atmospheric CO_2 concentrations were very high. This storing of carbon through the growth of plant matter, and its subsequent conversion to coal, oil, peat and gas, dramatically reduced atmospheric CO_2 levels and played an important role in cooling the planet to temperatures that could support advanced life forms. The concern now is that by unlocking this stored carbon climate change is being driven in the other direction, with global warming the direct result of an excessive greenhouse effect.

Ice core samples indicate that the level of carbon dioxide in the atmosphere was more or less stable at 280 parts per million (ppm) over the last few thousand years up to the onset of the industrial revolution at the beginning of the nineteenth century. Subsequently, atmospheric CO_2 levels rose, at first slowly as a result of coal burning but since the Second World War the release of CO_2 has accelerated reflecting the exploitation of a wider range of fossil fuels. Current CO_2 levels are 380 ppm and rising fast.

CO_2 is not the only pollutant created by fossil fuelled generation: combustion in air comprising 78% nitrogen by volume inevitably produces nitrogen oxides, NO, and NO_2 and N_2O, collectively known as NO_x; and any sulfur content of the fuel results in SO_x emissions. NO_x and SO_x together contribute to acid rain and as a result it is now common to reduce any SO_x emissions from fossil fuelled power stations through flue gas desulfurization. The downside of this is reduced thermodynamic efficiency and some resulting increase in CO_2 emissions.

World coal reserves are substantial, but coal is a less attractive fuel from the point of view of CO_2 emissions and also much more disruptive to extract. The cheapest coal is from opencast mines, but this process is immensely damaging to the environment. All forms of generation have some environmental impact, but these are not in general reflected in the cost of electricity; because of this, these additional environmental costs are known as *externalities*.

Externalities are consequences of activity that are not normally a part of the economic analysis; for example the cost to society of ill health or environmental damage arising from pollution caused by a specific generating plant is not directly charged to the operator, i.e. it is external to the microeconomics of the plant's operation. A number of European countries now seek to bring these externalities back into the economics of electricity generation by some kind of environmental levy or carbon tax. Carbon trading, discussed in detail in Chapter 7, is an alternative means of achieving this goal.

The nuclear cycle is of course not without externalities, although the environmental costs are highly contested, contributing as they do to the economic attractions or otherwise of nuclear power. Radioactive waste disposal, radioactive emissions and final decommissioning and disposal of radioactive reactor components are rarely fully accounted for and thus fall to an extent into the category of externalities. There are also issues concerned with environmental damage associated with uranium mining, but in this regard it is similar to coal. If nuclear power is to mitigate global emissions, it is of vital importance to assess accurately how much CO_2 will be displaced by nuclear power. This is a topic fraught with controversy. The well established 386 g CO_2/kWh contributed by gas fuelled power stations will be taken as the benchmark. The emissions for nuclear power are quoted as 11–22 by OECD, and 10–130 by ISA, University of Sydney [3]. If the upper figures are valid, the contribution of nuclear power to CO_2 mitigation may be seriously compromised. Clearly this is an issue that requires certainty.

1.2.2 The Science

The science of climate change is very well established and its primary goal is to understand the link between CO_2 and other greenhouse gas concentrations and temperature rise. Work in this area has been carried out by the *Intergovernmental Panel on Climate Change (IPCC)*, which was set up in 1988 by the World Meteorological Organisation and the United Nations Environment Programme. It involves scientists from 169 countries.

Figure 1.2 shows the changing average global temperature, from 1850 to 2005. The bold curve is the smoothed trend while the individual annual averages are shown as bars. The temperatures are shown relative to the average over 1861–1900. The earth has warmed by 0.7 °C since around 1900, bringing the global temperature to the warmest level in over 12 000 years. All ten warmest years on record have occurred since 1990 and there is considerable physical and biological evidence confirming climate change. Most climate models indicate that a doubling of greenhouse gases since the pre-industrial period is very likely to result in a rise between 2–5 °C in global mean temperatures. This increased level is likely to be reached between 2030 and 2060. If no action is taken concentrations would be more than treble pre-industrial levels by 2100, resulting in a warming of 3–10 °C according to the latest climate projections.

Although the relationship between CO_2 concentration, temperature change and undesirable climatic changes is very complex and thus hard to predict precisely, it is widely believed that the CO_2 concentrations have to be stabilized if damaging global warming is to be avoided.

The IPCC concluded in 2001 [4] that there is strong evidence that most of the warming observed over the last 50 years is *anthropogenic* in that it is attributed to human activities. This was supported by the Joint Statement of Science Academies (2005) and a report from the US Climate Change Science Programme (2006). An IPCC updated report which was published in 2007 confirmed this link with greater certainty. A summary of recent scientific research may be found in Reference [5].

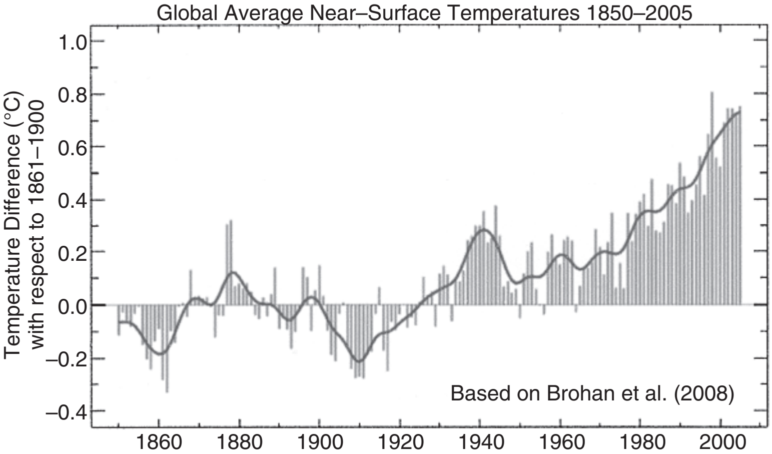

Figure 1.2 Temperature rise record. (© Crown copyright 2007, the Met Office)

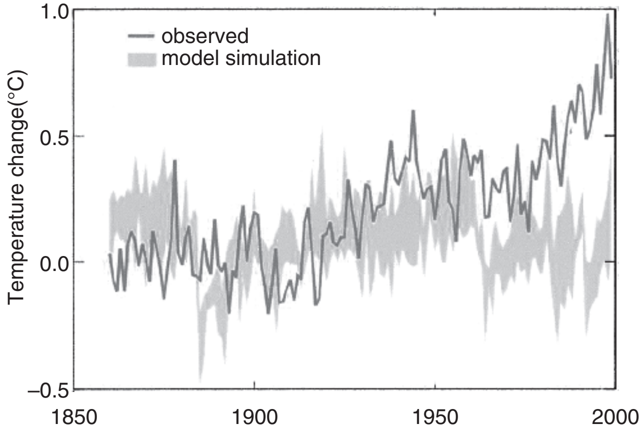

Figure 1.3 Natural factors cannot explain recent warming. (© Crown copyright 2007, the Met Office)

The basic evidence that provides confirmation that global warming is due to human-made factors was provided by a climate model developed at the Hadley Centre for Climate Prediction and Research in the UK. In Figure 1.3, the observed global temperature since the early 1900s is shown by the bold line. The climate model was driven over that period by natural factors such as output of the sun, changes in the optical depth of the atmosphere from volcanic emissions and the interactions between the atmosphere and oceans. The predictions of the model are shown by the fuzzy band. This clearly disagrees with the observations particularly since about 1970, that observed temperatures have risen by about 0.5 °C, but those simulated by natural factors have not changed at all.

If the climate model is now driven by natural factors as previously but in addition by man-made factors – change in greenhouse gas concentrations and sulfate particles – the model simulation predictions in Figure 1.4 are in much better agreement with the temperature record. Climate modelling studies by other research centres have arrived at the same broad conclusions.

1.2.3 The Kyoto Protocol

The effects of climate change are global and hence mitigation requires coordinated international effort. Signed in 1997, the Kyoto Protocol aims at reducing greenhouse gas emissions in the period 2008 to 2012 to 5.2% below those in 1990. Emissions of greenhouse gases by the US are currently 20% higher than in 1990 while the target figure in Kyoto was a cut of 7%. In the long run however it is prudent for industrialized countries to reduce their emissions by 60% by 2050 if the worst effects of climate change are to be mitigated with any confidence. This is a major challenge, to individuals, to governments and to supranational bodies. Greatest responsibility rests of course with the nations producing the largest CO_2 emissions per capita and those moving fast up the emissions table. Table 1.1 illustrates the variation in emissions per head and how this is partly driven by the income per head. Emissions from China are expected to surpass those of the US by 2025 so there is much to be done.

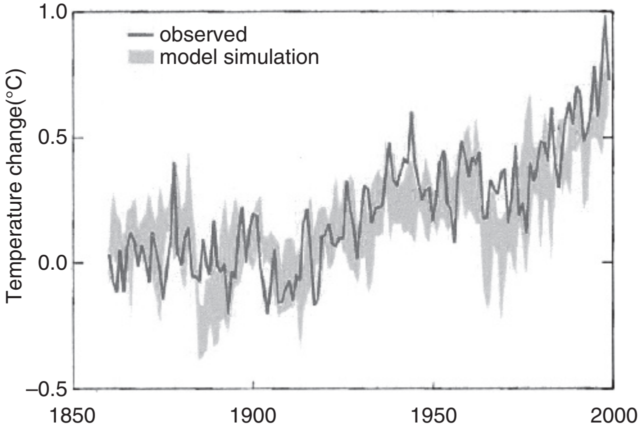

Figure 1.4 Climate warming can be simulated when man-made factors are included. (© Crown copyright 2007, the Met Office)

Table 1.1 Energy related CO_2 emissions. (Reproduced with permission from Climate Analysis Indicators Tool (CAIT) version 4.0 (or 5.0). World Resources Institute, 2007, available at http://cait.wri.org)

Country/grouping	CO_2 per head (tCO_2)	GDP per head ($)
USA	20.4	34 430
EU	9.4	23 577
UK	9.6	27 276
Japan	9.8	26 021
China	3.0	4 379
India	1.1	2 555
World	4.0	7 649

1.2.4 The Stern Report

The economics of climate change mitigation are crucial in steering an optimal policy towards a given agreed goal. These issues were addressed in the Stern Report [6].

Although the experts are almost universally convinced that climate change is taking place they are uncertain as to what exactly will be its effects. The Stern Report is unique in the sense that it examines the probabilities of reaching certain temperature thresholds at different stabilization levels. These probabilities have only been established recently and provide the basis for the economics of the analysis of the risks and costs involved in taking a range of actions towards reducing the greenhouse emissions.

The key message of the Stern Report is summarized below:

- The lags in the climate change process must be recognized. What is going to happen to the climate over the next 20–30 years is already determined and irreversible. Actions over the next 20–30 years will affect what happens in the decades to come.

- Climate change threatens the basic elements of life, i.e. access to water, food, health and the use of land and the environment.
- There is still time to avoid the worst impacts of climate change if action is taken now.
- Stabilization at 550 ppm of all greenhouse gases is recommended, but this would involve strong action.
- The costs of stabilizing the climate are significant (1% of global GDP) but manageable. Delay would be dangerous and much more expensive, perhaps as costly as 20% of global GDP.
- Action demands an international response.

The key actions should include:

- Increase in efficiency of energy use.
- Strict emissions trading rules to support the transition to low carbon development paths.
- Extensive use of renewable and other low carbon technologies.
- Technology cooperation and fivefold increased in low carbon technologies R&D.
- Reduction in deforestation.

The major focus of the Stern Report is the economics of climate stabilization. Figure 1.5 shows estimates of costs of low carbon technologies in 2015, 2025 and 2050 that may be used to constrain CO_2 emissions. The costs are expressed as a central estimate, with a range, and as a percentage of the fossil fuel alternative in the appropriate year. Due to learning effects the costs fall over time. The ranges reflect judgements about the probability distribution of unit costs and the variability of fossil fuel prices. The 0% line indicates that the costs are the same as the corresponding fossil fuel option. As expected, the uncertainties are large even for short term predictions. Onshore wind is shown to be particularly attractive with photovoltaic (PV) cells becoming very attractive beyond 2025.

On the basis of the costs of the low carbon technologies and assumptions on possible rates of uptake over time, the Stern Report estimates the distributions of emissions savings by technology for 2025 and 2050 for the desirable climate stabilization at 550 ppm. These estimates are shown in Figure 1.6. Energy efficiency and carbon capture and storage (CCS) play a major role in this scenario and will be discussed later in this chapter. Contributions from wind, solar, biofuels, hydro and distributed combined heat and power (dCHP) through electricity generation provide the remaining savings; and these are the technologies to be addressed in later chapters of this book.

1.2.5 Efficient Energy Use

Figure 1.6 stresses that efficiency measures are projected to make the largest contribution in climate change mitigation. It is therefore a surprise that the important topic of rational and efficient use of energy is rarely pursued vigorously in national or supranational plans in spite of the fact that study after study has shown that this route provides the most cost effective way to meet sustainability goals.

In most countries, regulations and financial incentives are now in place to encourage energy efficiency but their effect is modest and national energy consumption figures continue to

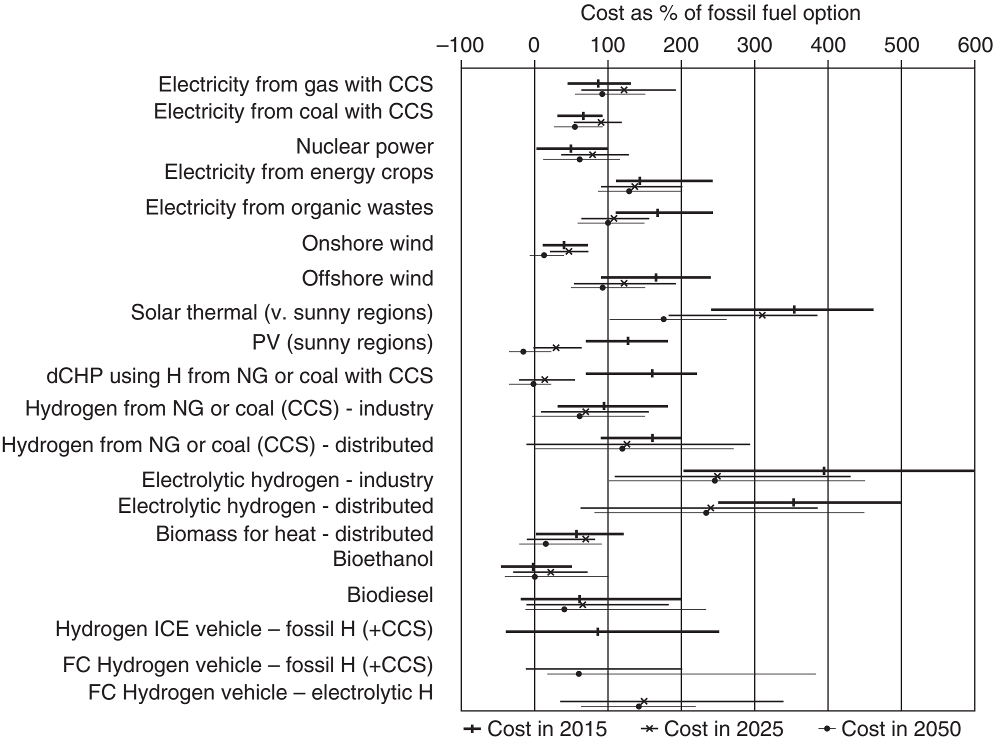

Figure 1.5 Unit costs of energy from low carbon technologies: CCS stands for carbon capture and storage, dCHP stands for distributed combined heat and power. (Reproduced from Stern review website, copyright Cambridge University Press)

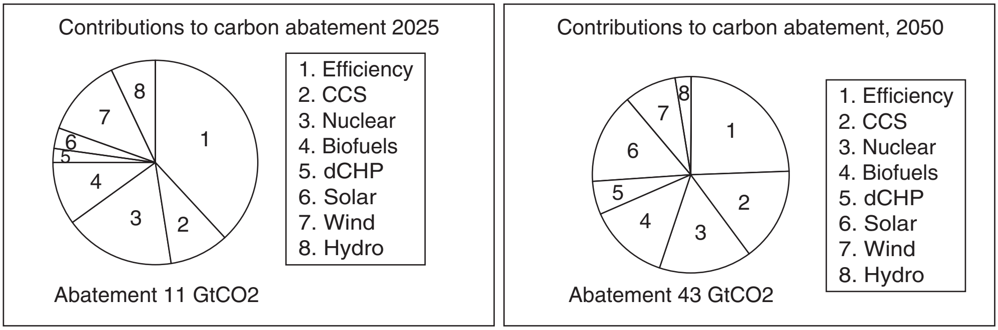

Figure 1.6 The distribution of emission savings by technology. (Reproduced from Stern Report, copyright Cambridge University Press)

rise year on year. Energy efficiency must be the linchpin of any future energy strategy because [7]:

- Using energy as efficiently as possible is the most cost effective way to manage energy demand, and thus to address carbon emissions. Saving energy is cheaper than making it.

- By reducing demand on gas and electricity distribution networks, energy efficiency will improve the security and resilience of these networks and reduce dependence on imported fuels.
- By reducing energy bills, energy efficiency will help businesses to be more productive and competitive.
- Improving the energy standards of homes has an important role in reducing spending on fuel by those in fuel poverty.

Increasing energy end use efficiency is unattractive for energy companies driven by commercial imperatives to increase sales and profits. It thus falls to governments to implement policies that change these drivers. Regulations can be put in place for example that require utilities to encourage customers to use electricity efficiently. A more revolutionary approach envisages the utility being transformed into a supplier of energy services, owning appliances in people's homes and thus being motivated to maximize the efficiency of these appliances. Whatever approach is finally adopted, the importance of reducing energy consumption should be the cornerstone of any CO_2 mitigation programme.

1.2.6 The Electricity Sector

Figure 1.7 shows the percentage of fuels used in the generation of electricity. Fossil fuels account for 64% of the fuels used in this sector with coal being the dominant source at approximately 40% and contributing nearly three quarters of CO_2 emissions. At present, large hydropower plants account for the major part of the renewables sector. Under half of the electricity produced is used in buildings, about a third in industry, under one-tenth in energy production (e.g. refineries) and less than one-tenth in transmission and distribution.

The world annual generation of electricity is in the region of 18 000 TWh representing an average rate of consumption of around 2000 GW. This electrical energy is generated in a very large collection of power stations driven mostly by fossil fuels. The electricity sector is the fastest growing source of emissions and estimated to increase fourfold between now and 2050. According to Stern this sector would need to be at least 60% decarbonized by 2050

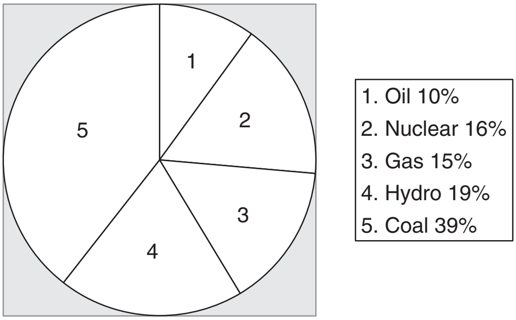

Figure 1.7 Contributions in the generation of electricity. (Data from Boyle, G., *Renewable Energy*, Oxford University Press, 2004)

for atmospheric concentration to stabilize at 550 ppm, thereby reducing the risk of catastrophic climate change.

1.2.7 Possible Solutions and Sustainability

Fundamental choices will have to be made in the years ahead. Societies are presently dependent on high and growing fossil fuel consumption. The possibility of weaning people from this dependence over a short timescale is completely unrealistic. The general shift in fossil fuels over the last two decades for both electricity generation and heating has been towards increased use of gas in place of coal, and to a lesser extent oil. This has helped to limit the growth in CO_2 emissions as gas combustion releases less CO_2 per unit of energy than coal. Political events, however, have generated anxiety in the EU and elsewhere in relation to increased dependence on this particular fuel.

A possible alternative path is to revert to dependence on coal. This resource is abundantly available in many developed counties including the US, Australia, many EU countries, Canada, Russia and in developing countries such as China, South Africa and Turkey. Recent developments in CO_2 capture or ‘sequestration’ for fossil fuels, discussed later in this chapter, give some hope that this source may be made more acceptable environmentally.

A number of potentially carbon neutral sources exist: these include nuclear fission (and possibly fusion in the far future) and all sources that derive directly or indirectly from the sun, namely biomass, wind, solar (thermal and photovoltaic), hydroelectric and marine. Geothermal and tidal energy are also carbon neutral and often regarded as renewable on the grounds that the sources are so huge as to be virtually inexhaustible. In Chapter 2, the characteristics of all these conventional and emerging technologies are discussed in some detail.

Finally, but no less important, other approaches essential in the move towards sustainability are a reduction in energy needs and improvements in the efficiency of energy use. The latter includes more efficient electricity generation. Although not the main focus of this book, these topics are briefly discussed in this chapter.

The planet’s reserves of fossil fuels and minerals are of course finite, and thus the exploitation of coal, oil, gas and uranium are not sustainable in the longer term. Fortunately, renewable energy (RE), being derived from naturally occurring energy flows, is inexhaustible and has no long term detrimental effect on the environment. As such it will in time become the basis of the energy supply system, and probably the sole means by which electricity is generated.

1.3 Generating Electricity

1.3.1 Conversion from other Energy Forms – the Importance of Efficiency

Figure 1.8 shows the ways in which various types of energy can be converted into electricity. At present, the path generating the bulk of electricity worldwide is shown by the bold lines that lead through combustion from chemical to thermal, from thermal to mechanical and finally to electrical power conversion. The bottleneck of this path is the limited thermodynamic efficiency determined by the Carnot cycle. Older thermal generating stations have

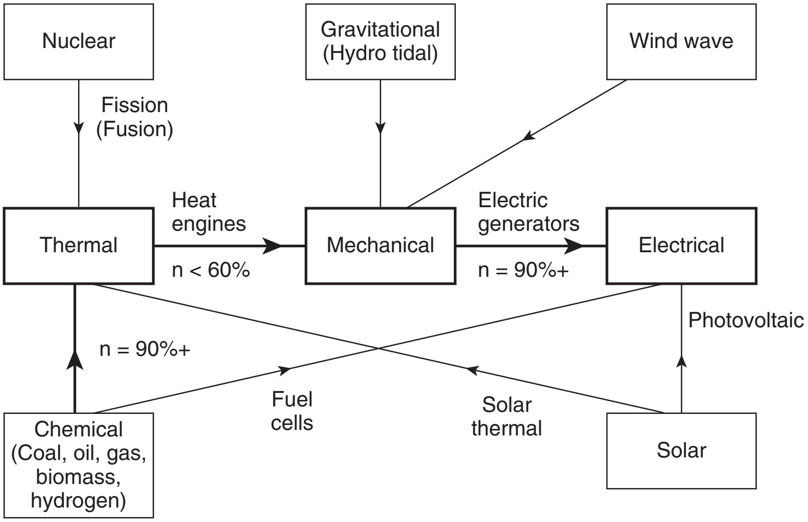

Figure 1.8 Conversion from a variety of energy forms into electricity

efficiencies between 35 and 40% although in the last two decades conversion has been substantially improved to over 50% through the development of combined cycle gas turbines (CCGTs) a technology discussed in Chapter 2. It follows that when coal, oil or gas is used only 35–50% of the primary energy is successfully converted, the remaining being discharged into the environment in the form of waste heat.

One way of getting around the Carnot limit is simply to make use of the waste heat. This is the principle of combined heat and power (CHP), used extensively in Scandinavia and of growing importance elsewhere. In such schemes, the waste energy from the thermal generation of electricity is distributed through heat mains to local industry and/or housing. This requires substantial infrastructure and is therefore only viable if the power station is reasonably close to the heat users. An alternative arrangement made possible by recent developments is to transport the fuel (mainly gas) to the consumer using the existing supply infrastructure and install the CHP system at the consumer's premises. Such systems are known as *micro-CHP* and are discussed in Chapter 8.

Direct paths that bypass the Carnot bottleneck are also available. The leading example of this approach is the fuel cell, which now borders on commercial viability in a number of forms: solid oxide, molten carbonate, and proton exchange membrane (PEM) to name the main ones. Another direct path is through photovoltaics, a technology that perhaps is the most promising in the near to far future.

The conversion efficiencies of the various routes indicated in Figure 1.8 are dealt with in greater detail in Chapter 2.

1.3.2 The Nuclear Path

The topic of electricity generation from nuclear power elicits strong emotions from supporters and critics. Although nuclear power supplies only the equivalent of 5.7% of the world primary energy at the time of writing this book, some believe this should be expanded massively. They argue that it is an attractive source of electricity, having very low carbon emissions.

After the Three Mile Island and the Chernobyl accidents there was a period of nearly ten years during which almost no new nuclear capacity was constructed. However, the recent concerns regarding fossil fuel security have prompted a number of countries to consider new building programmes. China and India are planning to build several tens of reactors each and the USA is posed to do the same. In contrast within Europe, only Finland has embarked on the construction of a new nuclear plant while, Sweden, Switzerland and Germany all have moratoriums in place leading to a phasing out of nuclear power. France on the other hand, remains committed to nuclear power which contributes about 80% of its present electricity needs.

In the UK the 2003 government White Paper was critical of the nuclear option, but by 2006, with concerns about a possible energy gap, the government's position had changed. It is now supportive in principal of a new nuclear programme. A key concern is that major investments in nuclear will deprive renewable energy sources of the finance they need to expand. Reflecting its importance, the debate over nuclear power is extensive and there is voluminous literature. Reference [8] provides a good entry point for those interested.

1.3.3 Carbon Capture and Storage

Figure 1.6 indicates, that according to Stern, by 2025 and 2050 about 20 and 40% respectively of carbon abatement is expected to be provided by the emerging technology of carbon capture and storage (CCS) provided that the technoeconomic and environmental issues can be satisfactorily dealt with. CCS has the significant advantage of reconciling the necessary use of fossil fuels in the medium term with the necessity of serious cuts in CO_2 emissions.

A large scale demonstration project was being planned in northeast Scotland, a joint venture by BP, Shell and ConocoPhilips [9]. Unfortunately, this project was recently abandoned, but the technology is being vigorously pursued in other projects worldwide. Figure 1.9 illustrates the geological storage options for CO_2.

With gas and oil prices likely to rise significantly, extracting CO_2-free energy from coal is also attracting substantial attention. Such technologies take a number of forms, but the so-called integrated gasification combined cycle (IGCC) process is in the forefront. This involves the production of a synthetic gas (syngas) obtained from coal through gasification. Syngas is composed mainly of hydrogen and carbon monoxide and is the fuel source to a high efficiency plant operating in the combined cycle mode. Buggenum, a 253 MW plant in the Netherlands operates on this principle and is the cleanest coal based plant in Europe. To date, no IGCC plant involving carbon capture has been built although this principle is to be used as a basis for a zero carbon emission 275 MW plant funded by the US Department of Energy which is being built and should be up and running in 2013.

1.3.4 Renewables

Figure 1.10 provides an overview of the earth's main energy paths that can be tapped to generate sustainable electricity. The main source of easily accessible renewable energy

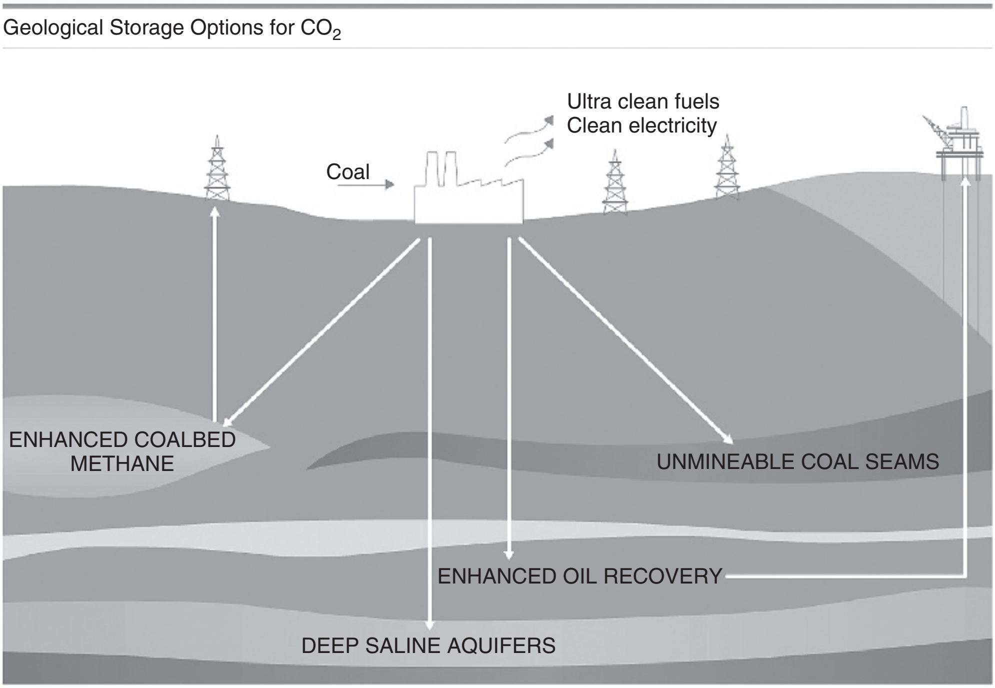

Figure 1.9 Geological storage options for CO_2. (Source: World Coal Institute)

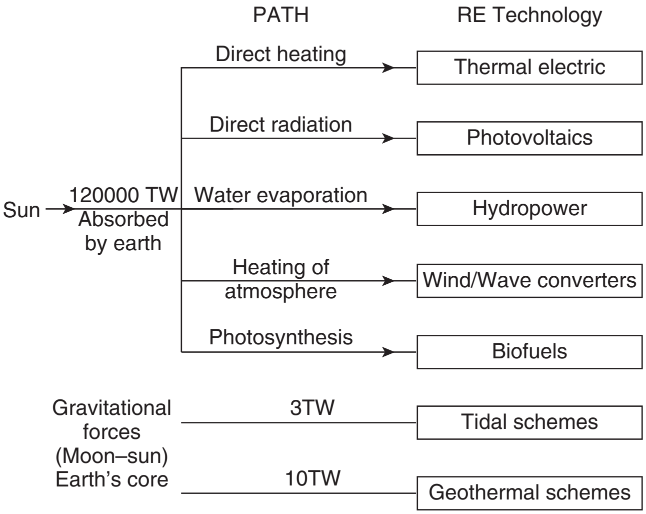

Figure 1.10 Renewable energy flow paths

is the sun. On average the rate of solar radiation intercepted by the earth's surface is about 8000 times as large as the average rate of world primary energy consumption. With the present world population this amounts to a staggering average power of 20 MW per person.

The figure shows that this energy flux can be accessed directly using solar thermal or photovoltaic technology, or indirectly in the form of wind, wave, hydro and biofuels. Two other energy sources are often regarded as renewable in view of their sustainable nature: energy in the tides caused by the gravitational fields of the moon and the sun which can be tapped using tidal barrages or tidal stream technology; and geothermal energy from the earth's core accessible in some locations through hot springs, geezers or boreholes. The available average power from these resources is a small fraction of that available from the sun.

A substantial proportion of the incident radiation is reflected back to space. Over the last several millennia and up to the onset of the industrial revolution, energy inputs and outputs have been in equilibrium at a global temperature level suitable for the development of the earth's biosphere. Exploiting the incident energy through the application of renewable energy technology *does not* disturb this balance. Intercepted natural energy flows, for example converted to electricity and then converted again by consumers into mechanical, chemical or light energy, all eventually degrade into heat.

Most renewable energy forms are readily converted to electricity. Solar energy, geothermal energy and biomass can also be used to supply heat. Renewable energy can in principal provide all the energy services available from conventional energy sources: heating, cooling, electricity and, albeit with some difficulty and cost, transport fuels. It has the additional advantage that being a naturally distributed resource, it can also provide energy to remote areas without the need for extensive energy transport systems. It is worth noting that it is not always necessary to convert the renewable energy into electricity. Solar water heating and wind-powered water pumping are fine examples of systems that can work very well without involving electricity at all. However, the major contribution that renewable energy will be increasingly making in supplying people's needs will be in electrical form.

Renewable energy is currently experiencing dramatic growth. Wind power and solar PV are leading the growth with global companies such as GE and Siemens entering the wind energy market, and BP and Shell playing a major role alongside Japanese companies like Sharpe and Sanyo in PV. In China five of the largest electrical aerospace and power generation equipment companies have recently begun to develop wind turbine technology. Most large oil companies have expanded their research and development in ethanol and biodiesel production from biomass. The fastest growing RE technology is currently grid connected PVs with 40% annual year on year growth, but the RE technology that has made the largest contribution to date (excluding conventional hydro) is wind power with over 60 GW installed in EU countries and 95 GW worldwide by the end of 2007.

At least 48 countries have national targets for RE supply including all 25 EU countries. Figure 1.11 shows the intended increase in contribution of the EU countries from 2002 to 2010. The EU has Europe-wide targets of 21% electricity and 12% of total energy by 2010. Table 1.2 shows the intentions of the EU over a wider period, with expected contributions in TW h per annum from various RE technologies.

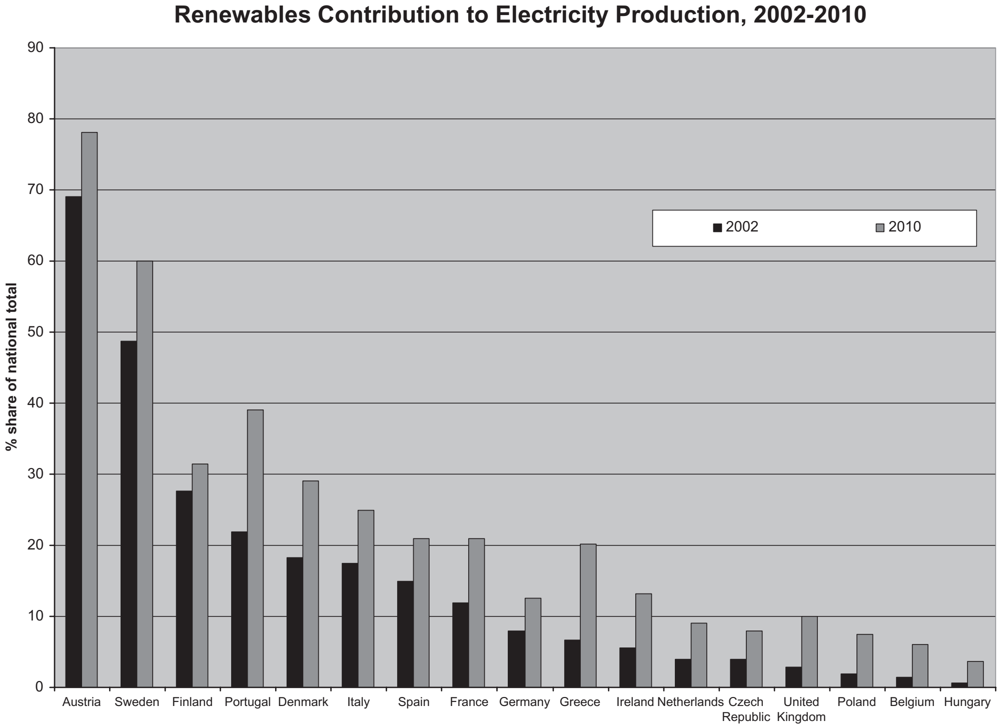

Figure 1.11 RE contribution to European electricity production. (Source: Oxford Intelligence)

Table 1.2 Contribution of renewables to electricity generation (1995–2020). (Source: Eurostat http://epp.eurostat.cec.eu.int)

	1995 Eurostat	2000 Eurostat	2010 Projections	2020 Projections
Wind (TWh)	4	22.4	168	444
Photovoltaics (TWh)	0.03	0.1	3.6	42
Biomass (TWh)	22.5	39.2	141	282
Hydro (TWh)	290	322	355	384
Geothermal (TWh)	3.5	4.8	7.0	14
Total RES in EU 15	320	388	675	1166
Total electricity[a] (TWh)	2308	2574	3027	3450
Share of RES (%)	13.9	15.1	22.3	33.8

[a] EU trends to 2030.

1.4 The Electrical Power System

1.4.1 Structure of the Electrical Power System

Electricity is widely used because it is a supremely flexible form of energy. It can be readily and efficiently transported and is easily converted to other forms of energy. Mechanical energy can be provided by very efficient motors, light energy by increasingly efficient light

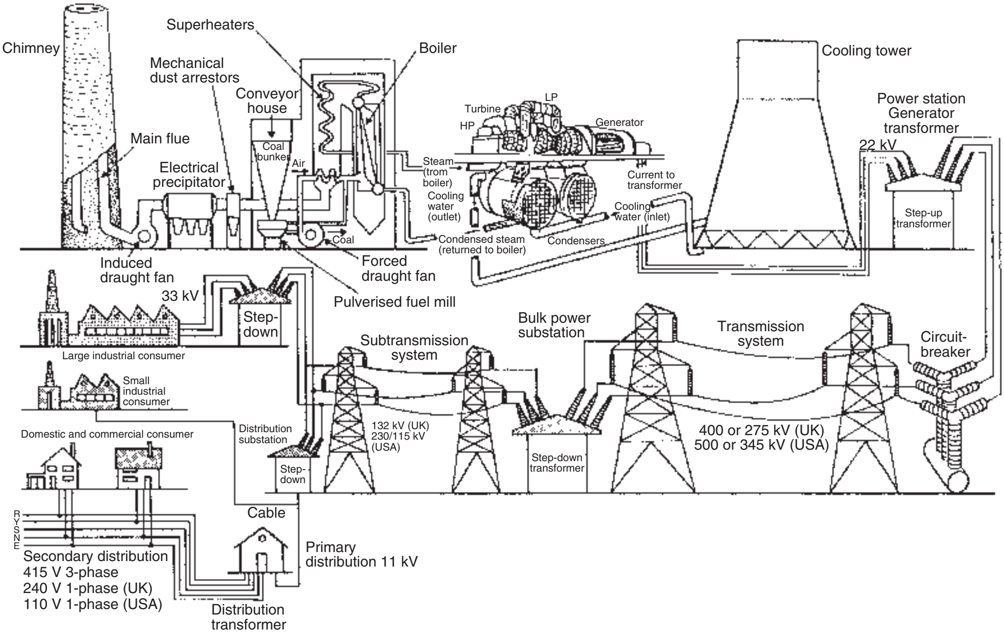

Figure 1.12 Pictorial view of the components of a large power system

fittings, heat energy by 100% efficient resistive elements, and power supply to electronic and IT (information technology) hardware through very efficient power conditioning units.

Figure 1.12 shows a diagrammatic layout of a typical electrical power system from the point of generation to the point of consumption. The figure depicts a coal fired power station as this represents the majority of world stations. The energy conversion chain follows the chemical → thermal → mechanical → electrical path depicted in Figure 1.8. Coal is pulverized and fed into a boiler where it is mixed with forced air and combusted. The boiler is a complex structure consisting of many stages of energy extraction from the combusted fuel. The flue gases are guided through equipment that removes solid particles and sulfur (desulfurization is not shown in the figure) before being released into the atmosphere. The highly purified water in the boiler is converted into superheated steam which is passed through several turbine stages on the shaft of a turbogenerator. The low pressure low temperature steam from the outlet of the turbine is condensed into the purified water which in this closed system is pumped back into the boiler. The condensing process unfortunately needs a substantial amount of external cooling water. In the figure, this water is provided from a pond at the bottom of a cooling tower. The hot water from the condenser is sprayed at the top of the tower and transfers its heat to the air that passes up the venturi shaped tower. The lost water must be made up from some external source such as a local river.

The energy generated at the power stations is transmitted to consumers by overhead transmission lines and underground cables that possess ohmic resistance. The energy loss due to the unavoidable resistive heating of a line or cable is proportional to the square of the current I it carries. Additionally, for a given power transfer, which is proportional to VI, the current is inversely proportional to the voltage (other things being equal). Thus, the loss decreases with the square of the voltage V. The downside of operating at higher voltages is that costs of insulation and other power system equipment increase substantially. Thus, for bulk transmission of power over long distances, higher voltages are most economic whereas, for local distribution of modest power to numerous connection points, lower voltages are most economic. The economics also dictate that it is worthwhile to have several intermediate voltages. This multiple voltage arrangement results in network transmission losses confined to within 5–10% of the throughput power.

The bulk of global electricity is generated in large (>500 MW) power stations at around 20 kV. This is then stepped up by transformers to an extra high voltage (EHV) level such as 400 kV and carried by the transmission system to the bulk supply points, where it is stepped down to a high voltage (HV) level of around 100 kV. Some very large industrial consumers are connected at this level but most power is transformed down again to medium voltage (MV) levels such as 30 kV, then to 10 kV and finally to the low voltage (LV) level of 400 V, also referred to as the distribution system, which provides 230 V, when the connection is single-phase. In the USA and a few other countries, the LV level is 200 V three-phase, 115 V single-phase. The voltages used vary from country to country but the power system structure follows closely the layout of Figure 1.12.

In Figure 1.12, a circuit-breaker is shown after the generator step-up transformer. This is a component part of an extensive protection network which permeates all levels of the power system. Faults on the network may result in low resistance paths that cause excessive currents capable of damaging equipment. The protection devices, circuit breakers at high voltage levels and fuses at domestic distribution level, operate to isolate the faulty part of the network and prevent equipment damage. The effect on the protection system of introducing renewable energy sources will be discussed in Chapter 6.

1.4.2 Integrating Renewables into Power Systems

The term *grid* is often used loosely to describe the totality of the network. In particular, *grid connected* means connected to any part of the network The term *national grid* usually means the EHV transmission network.

Integration specifically means the physical connection of the generator to the network with due regard to the secure and safe operation of the system and the control of the generator so that the energy resource is exploited optimally. The proper integration of any electrical generator into an electrical power system requires knowledge of the well-established principles of electrical engineering. The integration of generators powered from renewable energy sources is fundamentally similar to that of fossil fuelled powered generators and is based on the same principles, but, renewable energy sources are often variable and geographically dispersed.

A renewable energy generator may be described either as *standalone* or *grid-connected.* In a standalone system a renewable energy generator (with or without other back-up generators or storage) supplies the greater part of the demand. In a grid-connected system, the renewable energy generator feeds power to a large interconnected grid, also fed by a variety of other generators. The crucial distinction here is that the power injected by the renewable energy generator is only a small fraction of that generated by the totality of generators on the grid. The distinction between standalone and grid-connected generators is a useful one but is not always clear-cut. Sometimes confusion arises when the word grid is used to refer to a relatively small standalone electrical network. This is not necessarily wrong (though it may indicate delusions of grandeur!) but it should always be clear as to the extent of the grid being referred to.

The point on the network to which a renewable energy generator is connected is referred to, for reasons to be explained later, as the *point of common coupling* (PCC).

1.4.3 Distributed Generation

Power systems have developed over the years to supply a varying demand from centralized generation sourced from fossil and nuclear fuels. Unless nuclear fusion proves successful, which will not be known for over 50 years, there is universal agreement that by the end of this century the majority of our electrical energy will be supplied from RE sources.

Generators powered from renewable energy sources (except large scale hydro and large offshore and onshore wind farms) are typically much smaller than the fossil fuelled and nuclear powered generators that dominate today's large power systems. Small generators cannot be connected to the transmission system because of the cost of high voltage transformers and switchgear. Also, the transmission system is often a long way away as the geographical location of the generator is constrained by the geographical availability of the resource. Small generators must therefore be connected to the distribution network. Such generation is known as *distributed* or *dispersed generation*. It is also known as *embedded generation* as it is embedded in the distribution network.

In traditional power systems power invariably flows from the large centralized power stations connected to the EHV network down through the HV and LV systems to be distributed to consumers. In power systems with distributed generation power may travel from point to point within the distribution system. This unusual flow pattern has some serious implications in the effective operation and protection of the distribution network. Distributed generation will be discussed in Chapter 6.

It may be concluded that present power systems will gradually have to evolve and adapt so that, in the far future, a managed demand will be supplied from distributed, mostly variable, RE generation. This transformation will be aided by the liberal use of power electronic interfaces capable of maximizing the effectiveness of RE sources, controlling power flows and ensuring reliability of supply. Some of these issues are discussed in the last chapter.

1.4.4 RE Penetration

The proportion of electrical energy or power being supplied from renewable sources is generally referred to as the *penetration*. It is usually expressed as a percentage. When fuel or CO_2-emission savings are being considered, it is useful to consider the *average penetration*:

$$\text{Average penetration} = \frac{\text{Energy from renewable energy powered generators (kW h)}}{\text{Total energy delivered to loads (kW h)}}$$

In this case, the energy (kWh) is measured over a long period of time, perhaps a year. At first sight, it might seem more natural to express the denominator (total energy delivered to loads) as: total energy from all the generators (including fossil fuelled generators). However, in standalone systems, there may be *dump loads* (loads where energy is dumped as heat) to consider and, in grid-connected systems, there is often interest in the penetration in a given geographical area, in which case it may be termed the *local penetration*.

For other purposes, including system control, it is necessary to consider the instantaneous penetration:

$$\text{Instantaneous Penetration} = \frac{\text{Power from renewable energy powered generators (kW)}}{\text{Total power delivered to loads (kW)}}$$

Since the electrical output from some generators operating from renewable energy sources is variable, the maximum instantaneous penetration will normally be much higher than the average penetration.

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