Chapter 1

Principles of renewable energy

1.1 Introduction

The aim of this text is to analyse the full range of renewable energy supplies available for modern economies. Such renewables are recognised as vital inputs for sustainability and so encouraging their growth is significant. Subjects will include power from wind, water, biomass, sunshine and other such continuing sources, including wastes. Although the scale of local application ranges from tens to many millions of watts, and the totality is a global resource, four questions are asked for practical application:

1 How much energy is available in the immediate environment – what is the resource?
2 For what purposes can this energy be used – what is the end-use?
3 What is the environmental impact of the technology – is it sustainable?
4 What is the cost of the energy – is it cost-effective?

The first two are technical questions considered in the central chapters by the type of renewables technology. The third question relates to broad issues of planning, social responsibility and sustainable development; these are considered in this chapter and in Chapter 17. The environmental impacts of specific renewable energy technologies are summarised in the last section of each technology chapter. The fourth question, considered with other institutional factors in the last chapter, may dominate for consumers and usually becomes the major criterion for commercial installations. However, cost-effectiveness depends significantly on:

a Appreciating the *distinctive scientific principles* of renewable energy (Section 1.4).
b Making each stage of the energy supply process *efficient* in terms of both minimising losses and maximising economic, social and environmental benefits.
c Like-for-like *comparisons*, including externalities, with fossil fuel and nuclear power.

When these conditions have been met, it is possible to calculate the costs and benefits of a particular scheme and compare these with alternatives for an economic and environmental assessment.

Failure to understand the distinctive scientific principles for harnessing renewable energy will almost certainly lead to poor engineering and uneconomic operation. Frequently there will be a marked contrast between the methods developed for renewable supplies and those used for the non-renewable fossil fuel and nuclear supplies.

1.2 Energy and sustainable development

1.2.1 Principles and major issues

Sustainable development can be broadly defined as living, producing and consuming in a manner that meets the needs of the present without compromising the ability of future generations to meet their own needs. It has become a key guiding principle for policy in the 21st century. Worldwide, politicians, industrialists, environmentalists, economists and theologians affirm that the principle must be applied at international, national and local level. Actually applying it in practice and in detail is of course much harder!

In the international context, the word 'development' refers to improvement in quality of life, and, especially, standard of living in the less developed countries of the world. The aim of sustainable development is for the improvement to be achieved whilst maintaining the ecological processes on which life depends. At a local level, progressive businesses aim to report a positive *triple bottom line*, i.e. a positive contribution to the *economic, social and environmental* well-being of the community in which they operate.

The concept of sustainable development became widely accepted following the seminal report of the World Commission on Environment and Development (1987). The commission was set up by the United Nations because the scale and unevenness of economic development and population growth were, and still are, placing unprecedented pressures on our planet's lands, waters and other natural resources. Some of these pressures are severe enough to threaten the very survival of some regional populations and, in the longer term, to lead to global catastrophes. Changes in lifestyle, especially regarding production and consumption, will eventually be forced on populations by ecological and economic pressures. Nevertheless, the economic and social pain of such changes can be eased by foresight, planning and political (i.e. community) will.

Energy resources exemplify these issues. Reliable energy supply is essential in all economies for lighting, heating, communications, computers, industrial equipment, transport, etc. Purchases of energy account for 5–10% of gross national product in developed economies. However, in some developing countries, energy imports may have cost over half the value of total exports; such economies are unsustainable and an economic challenge for sustainable development. World energy use increased more than tenfold over the 20th century, predominantly from fossil fuels (i.e. coal, oil and gas) and with the addition of electricity from nuclear power. In the 21st century, further increases in world energy consumption can be expected, much for rising industrialisation and demand in previously less developed countries, aggravated by gross inefficiencies in all countries. Whatever the energy source, there is an overriding need for efficient generation and use of energy.

Fossil fuels are not being newly formed at any significant rate, and thus present stocks are ultimately finite. The location and the amount of such stocks depend on the latest surveys. Clearly the dominant fossil fuel type by mass is coal, with oil and gas much less. The reserve lifetime of a resource may be defined as the known accessible amount divided by the rate of present use. By this definition, the lifetime of oil and gas resources is usually only a few decades; whereas lifetime for coal is a few centuries. Economics predicts that as the lifetime of a fuel reserve shortens, so the fuel price increases; consequently demand for that fuel reduces and previously more expensive sources and alternatives enter the market. This process tends to make the original source last longer than an immediate calculation indicates. In practice, many other factors are involved, especially governmental policy and international relations. Nevertheless, the basic geological fact remains: fossil fuel reserves are limited and so the present patterns of energy consumption and growth are not sustainable in the longer term.

Moreover, it is the *emissions* from fossil fuel use (and indeed nuclear power) that increasingly determine the fundamental limitations. Increasing concentration of CO_2 in the Atmosphere is such an example. Indeed, from an ecological understanding of our Earth's long-term history over billions of years, carbon was in excess in the Atmosphere originally and needed to be sequestered below ground to provide our present oxygen-rich atmosphere. Therefore from arguments of: (i) the finite nature of fossil and nuclear fuel materials, (ii) the harm of emissions and (iii) ecological sustainability, it is essential to expand renewable energy supplies and to use energy more efficiently. Such conclusions are supported in economics if the full external costs of both obtaining the fuels and paying for the damage from emissions are internalised in the price. Such fundamental analyses may conclude that renewable energy and the efficient use of energy are cheaper for society than the traditional use of fossil and nuclear fuels.

The detrimental environmental effects of burning the fossil fuels likewise imply that current patterns of use are unsustainable in the longer term. In particular, CO_2 emissions from the combustion of fossil fuels have significantly raised the concentration of CO_2 in the Atmosphere. The balance of scientific opinion is that if this continues, it will enhance the *greenhouse* *effect*[1] and lead to significant *climate change* within a century or less, which could have major adverse impact on food production, water supply and human, e.g. through floods and cyclones (IPCC). Recognising that this is a global problem, which no single country can avert on its own, over 150 national governments signed the UN Framework Convention on Climate Change, which set up a framework for concerted action on the issue. Sadly, concrete action is slow, not least because of the reluctance of governments in industrialised countries to disturb the lifestyle of their voters. However, potential climate change, and related sustainability issues, is now established as one of the major drivers of energy policy.

In short, renewable energy supplies are much more compatible with sustainable development than are fossil and nuclear fuels, in regard to both resource limitations and environmental impacts (see Table 1.1).

Consequently almost all national energy plans include four vital factors for improving or maintaining social benefit from energy:

1 increased harnessing of renewable supplies
2 increased efficiency of supply and end-use
3 reduction in pollution
4 consideration of lifestyle.

1.2.2 A simple numerical model

Consider the following simple model describing the need for commercial and non-commercial energy resources:

$$R = EN \tag{1.1}$$

Here R is the total yearly energy requirement for a population of N people. E is the per capita energy-use averaged over one year, related closely to provision of food and manufactured goods. The unit of E is energy per unit time, i.e. power. On a world scale, the dominant supply of energy is from commercial sources, especially fossil fuels; however, significant use of non-commercial energy may occur (e.g. fuel wood, passive solar heating), which is often absent from most official and company statistics. In terms of total commercial energy use, the average per capita value of E worldwide is about 2 kW; however, regional average values range widely, with North America 9 kW, Europe as a whole 4 kW, and several regions of Central Africa as small as 0.1 kW. The inclusion of non-commercial energy increases

1 As described in Chapter 4, the presence of CO_2 (and certain other gases) in the atmosphere keeps the Earth some 30 degrees warmer than it would otherwise be. By analogy with horticultural greenhouses, this is called the 'greenhouse effect'.

Table 1.1 Comparison of renewable and conventional energy systems

	Renewable energy supplies (green)	*Conventional energy supplies (brown)*
Examples	Wind, solar, biomass, tidal	Coal, oil, gas, radioactive ore
Source	Natural local environment	Concentrated stock
Normal state	A current or flow of energy. An income	Static store of energy. Capital
Initial average intensity	Low intensity, dispersed: $\leq 300\,W\,m^{-2}$	Released at $\geq 100\,kW\,m^{-2}$
Lifetime of supply	Infinite	Finite
Cost at source	Free	Increasingly expensive.
Equipment capital cost per kW capacity	Expensive, commonly $\approx$US\$1000 kW^{-1}	Moderate, perhaps \$500 kW^{-1} without emissions control; yet expensive >US\$1000 kW^{-1} with emissions reduction
Variation and control	Fluctuating; best controlled by change of load using positive feedforward control	Steady, best controlled by adjusting source with negative feedback control
Location for use	Site- and society-specific	General and invariant use
Scale	Small and moderate scale often economic, large scale may present difficulties	Increased scale often improves supply costs, large scale frequently favoured
Skills	Interdisciplinary and varied. Wide range of skills. Importance of bioscience and agriculture	Strong links with electrical and mechanical engineering. Narrow range of personal skills
Context	Bias to rural, decentralised industry	Bias to urban, centralised industry
Dependence	Self-sufficient and 'islanded' systems supported	Systems dependent on outside inputs
Safety	Local hazards possible in operation: usually safe when out of action	May be shielded and enclosed to lessen great potential dangers; most dangerous when faulty
Pollution and environmental damage	Usually little environmental harm, especially at moderate scale Hazards from excess biomass burning Soil erosion from excessive biofuel use Large hydro reservoirs disruptive Compatible with natural ecology	Environmental pollution intrinsic and common, especially of air and water Permanent damage common from mining and radioactive elements entering water table. Deforestation and ecological sterilisation from excessive air pollution Climate change emissions
Aesthetics, visual impact	Local perturbations may be unpopular, but usually acceptable if local need perceived	Usually utilitarian, with centralisation and economy of large scale

all these figures and has the major proportional benefit in countries where the value of E is small.

Standard of living relates in a complex and an ill-defined way to E. Thus per capita gross national product S (a crude measure of standard of living) may be related to E by:

$$S = fE \tag{1.2}$$

Here f is a complex and non-linear coefficient that is itself a function of many factors. It may be considered an efficiency for transforming energy into wealth and, by traditional economics, is expected to be as large as possible. However, S does not increase uniformly as E increases. Indeed S may even decrease for large E (e.g. because of pollution or technical inefficiency). Obviously unnecessary waste of energy leads to a lower value of f than would otherwise be possible. Substituting for E in (1.1), the national requirement for energy becomes:

$$R = \frac{(SN)}{f} \tag{1.3}$$

so

$$\frac{\Delta R}{R} = \frac{\Delta S}{S} + \frac{\Delta N}{N} - \frac{\Delta f}{f} \tag{1.4}$$

Now consider substituting global values for the parameters in (1.4). In 50 years the world population N increased from 2500 million in 1950 to over 6000 million in 2000. It is now increasing at approximately 2–3% per year so as to double every 20–30 years. Tragically, high infant mortality and low life expectancy tend to hide the intrinsic pressures of population growth in many countries. Conventional economists seek exponential growth of S at 2–5% per year. Thus in (1.4), at constant efficiency f, the growth of total world energy supply is effectively the sum of population and economic growth, i.e. 4–8% per year. Without new supplies such growth cannot be maintained. Yet at the same time as more energy is required, fossil and nuclear fuels are being depleted and debilitating pollution and climate change increase; so an obvious conclusion to overcome such constraints is to increase renewable energy supplies. Moreover, from (1.3) and (1.4), it is most beneficial to increase the parameter f, i.e. to have a positive value of $\dot{f}$. Consequently there is a growth rate in energy efficiency, so that S can increase, while R decreases.

1.2.3 Global resources

Considering these aims, and with the most energy-efficient modern equipment, buildings and transportation, a justifiable target for energy use in a modern society with an appropriate lifestyle is $E = 2\,\text{kW}$ per person. Such a target is consistent with an energy policy of 'contract and converge' for global equity, since worldwide energy supply would total approximately the present global average usage, but would be consumed for a far higher standard of living. Is this possible, even in principle, from renewable energy? Each square metre of the earth's habitable surface is crossed by, or accessible to, an average energy flux from all renewable sources of about 500 W (see Problem 1.1). This includes solar, wind or other renewable energy forms in an overall estimate. If this flux is harnessed at just 4% efficiency, 2 kW of power can be drawn from an area of $10\,\text{m} \times 10\,\text{m}$, assuming suitable methods. Suburban areas of residential towns have population densities of about 500 people per square kilometre. At 2 kW per person, the total energy demand of $1000\,\text{kW}\,\text{km}^{-2}$ could be obtained in principle by using just 5% of the local land area for energy production. Thus renewable energy supplies can provide a satisfactory standard of living, but only if the technical methods and institutional frameworks exist to extract, use and store the energy in an appropriate form at realistic costs. This book considers both the technical background of a great variety of possible methods and a summary of the institutional factors involved. Implementation is then everyone's responsibility.

1.3 Fundamentals

1.3.1 Definitions

For all practical purposes energy supplies can be divided into two classes:

1. *Renewable energy*. 'Energy obtained from natural and persistent flows of energy occurring in the immediate environment'. An obvious example is solar (sunshine) energy, where 'repetitive' refers to the 24-hour major period. Note that the energy is already passing through the environment as a *current* or *flow*, irrespective of there being a device to intercept and harness this power. Such energy may also be called *Green Energy* or *Sustainable Energy*.
2. *Non-renewable energy*. 'Energy obtained from static stores of energy that remain underground unless released by human interaction'. Examples are nuclear fuels and fossil fuels of coal, oil and natural gas. Note that the energy is initially an isolated energy *potential*, and external action is required to initiate the supply of energy for practical purposes. To avoid using the ungainly word 'non-renewable', such energy supplies are called *finite supplies* or *Brown Energy*.

These two definitions are portrayed in Figure 1.1. Table 1.1 provides a comparison of renewable and conventional energy systems.

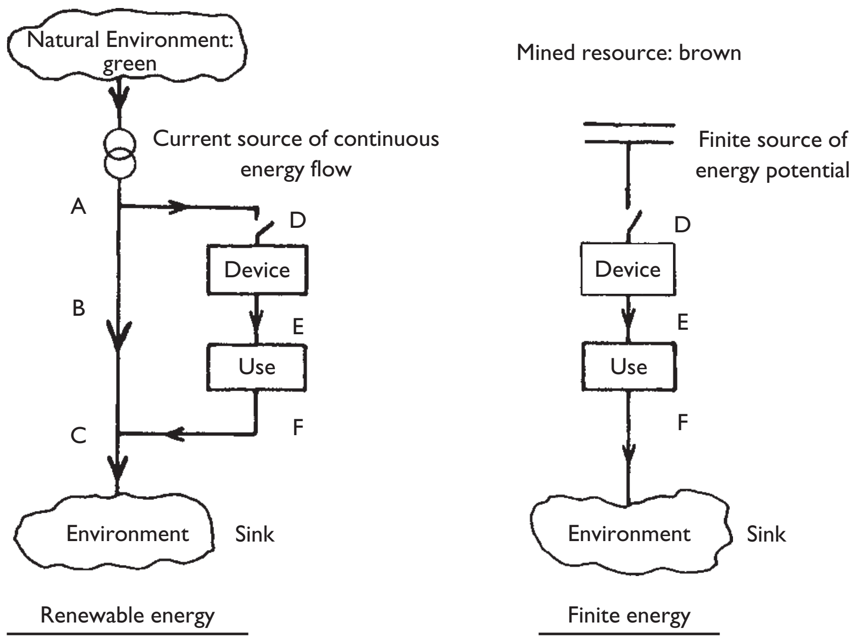

Figure 1.1 Contrast between renewable (green) and finite (brown) energy supplies. Environmental energy flow ABC, harnessed energy flow DEF.

1.3.2 Energy sources

There are five ultimate primary sources of useful energy:

1 The Sun.
2 The motion and gravitational potential of the Sun, Moon and Earth.
3 Geothermal energy from cooling, chemical reactions and radioactive decay in the Earth.
4 Human-induced nuclear reactions.
5 Chemical reactions from mineral sources.

Renewable energy derives continuously from sources 1, 2 and 3 (aquifers). Finite energy derives from sources 1 (fossil fuels), 3 (hot rocks), 4 and 5. The sources of most significance for global energy supplies are 1 and 4. The fifth category is relatively minor, but useful for primary batteries, e.g. dry cells.

1.3.3 Environmental energy

The flows of energy passing continuously as renewable energy through the Earth are shown in Figure 1.2. For instance, total solar flux absorbed at sea level is about 1.2×10^{17} W. Thus the solar flux reaching the Earth's surface is ~20 MW per person; 20 MW is the power of ten very large

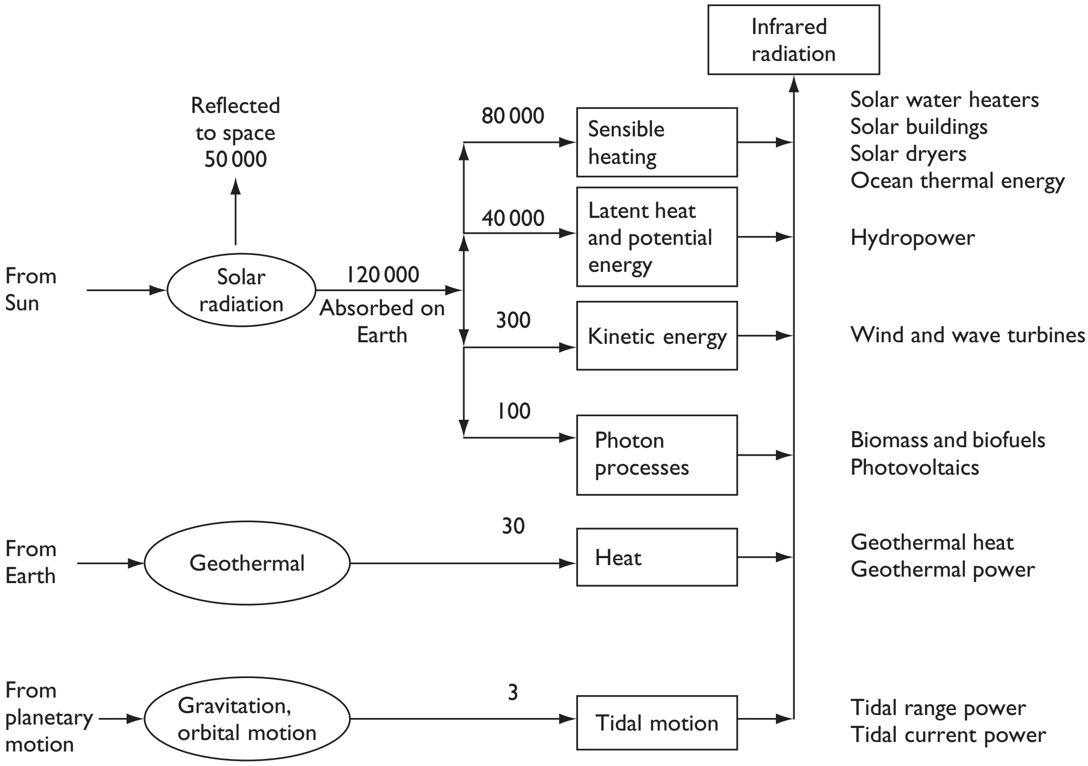

Figure 1.2 Natural energy currents on earth, showing renewable energy system. Note the great range of energy flux ($1:10^5$) and the dominance of solar radiation and heat. Units terawatts (10^{12} W).

diesel electric generators, enough to supply all the energy needs of a town of about 50 000 people. The maximum solar flux density (irradiance) perpendicular to the solar beam is about $1\,\mathrm{kW\,m^{-2}}$; a very useful and easy number to remember. In general terms, a human being is able to intercept such an energy flux without harm, but any increase begins to cause stress and difficulty. Interestingly, power flux densities of $\sim 1\,\mathrm{kW\,m^{-2}}$ begin to cause physical difficulty to an adult in wind, water currents or waves.

However, the global data of Figure 1.2 are of little value for practical engineering applications, since particular sites can have remarkably different environments and possibilities for harnessing renewable energy. Obviously flat regions, such as Denmark, have little opportunity for hydro-power but may have wind power. Yet neighbouring regions, for example Norway, may have vast hydro potential. Tropical rain forests may have biomass energy sources, but deserts at the same latitude have none (moreover, forests must not be destroyed so making more deserts). Thus practical renewable energy systems have to be matched to particular local environmental energy flows occurring in a particular region.

1.3.4 Primary supply to end-use

All energy systems can be visualised as a series of pipes or circuits through which the energy currents are channelled and transformed to become useful in domestic, industrial and agricultural circumstances. Figure 1.3(a) is a Sankey diagram of energy supply, which shows the energy flows through a national energy system (sometimes called a 'spaghetti diagram' because of its appearance). Sections across such a diagram can be drawn as pie charts showing primary energy supply and energy supply to end-use

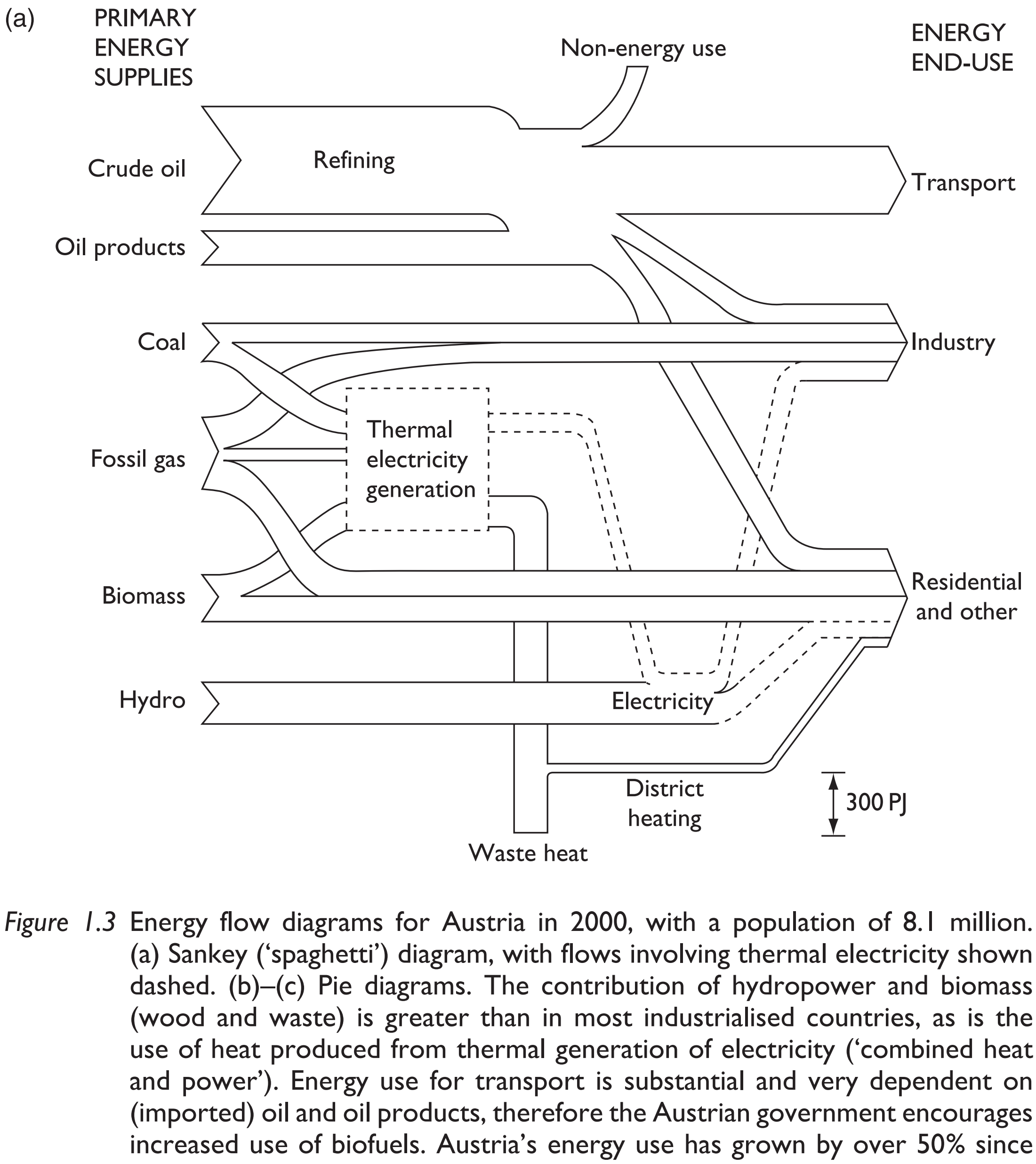

Figure 1.3 Energy flow diagrams for Austria in 2000, with a population of 8.1 million. (a) Sankey ('spaghetti') diagram, with flows involving thermal electricity shown dashed. (b)–(c) Pie diagrams. The contribution of hydropower and biomass (wood and waste) is greater than in most industrialised countries, as is the use of heat produced from thermal generation of electricity ('combined heat and power'). Energy use for transport is substantial and very dependent on (imported) oil and oil products, therefore the Austrian government encourages increased use of biofuels. Austria's energy use has grown by over 50% since 1970, although the population has grown by less than 10%, indicating the need for greater efficiency of energy use. [Data source: simplified from International Energy Agency, *Energy Balances of OECD countries 2000–2001*.]

(b)

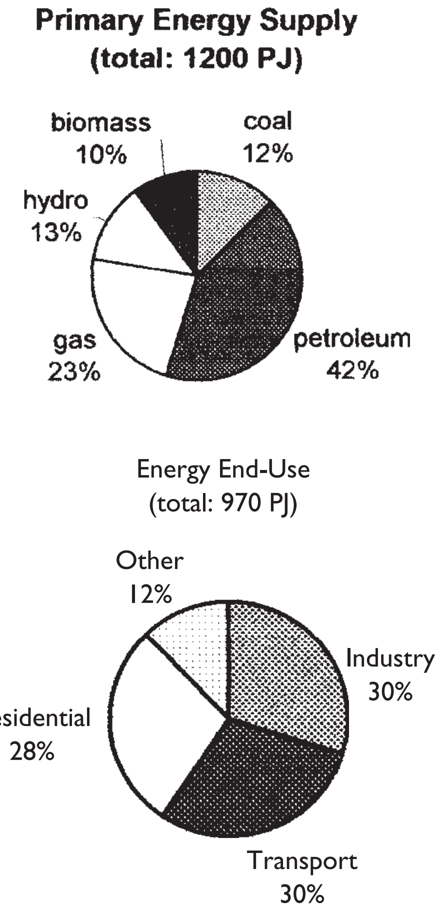

Figure 1.3 (Continued).

(Figure 1.3(b)). Note how the total energy end-use is less than the primary supply because of losses in the transformation processes, notably the generation of electricity from fossil fuels.

1.3.5 Energy planning

1 *Complete energy systems* must be analysed, and supply should not be considered separately from end-use. Unfortunately precise *needs* for energy are too frequently forgotten, and supplies are not well matched to end-use. Energy losses and uneconomic operation therefore frequently result. For instance, if a dominant domestic energy requirement is heat for warmth and hot water, it is irresponsible to generate grid quality electricity from a fuel, waste the majority of the energy as thermal emission from the boiler and turbine, distribute the electricity in lossy cables and then dissipate this electricity as heat. Sadly

such inefficiency and disregard for resources often occurs. Heating would be more efficient and cost-effective from direct heat production with local distribution. Even better is to combine electricity generation with the heat production using CHP – combined heat and power (electricity).

2 *System efficiency* calculations can be most revealing and can pinpoint unnecessary losses. Here we define 'efficiency' as the ratio of the useful energy output from a process to the total energy input to that process. Consider electric lighting produced from 'conventional' thermally generated electricity and lamps. Successive energy efficiencies are: electricity generation ~30%, distribution ~90% and incandescent lighting (energy in visible radiation, usually with a light-shade) 4–5%. The total efficiency is 1–1.5%. Contrast this with cogeneration of useful heat and electricity (efficiency ~85%), distribution (~90%) and lighting in modern low consumption compact fluorescent lamps (CFL) (~22%). The total efficiency is now 14–18%; a more than tenfold improvement! The total life cycle cost of the more efficient system will be much less than for the conventional, despite higher per unit capital costs, because (i) less generating capacity and fuel are needed, (ii) less per unit emission costs are charged, and (iii) equipment (especially lamps) lasts longer (see Problems 1.2 and 1.3).

3 *Energy management* is always important to improve overall efficiency and reduce economic losses. No energy supply is free, and renewable supplies are usually more expensive in practice than might be assumed. Thus there is no excuse for wasting energy of any form unnecessarily. Efficiency with finite fuels reduces pollution; efficiency with renewables reduces capital costs.

1.4 Scientific principles of renewable energy

The definitions of renewable (green) and finite (brown) energy supplies (Section 1.3.1) indicate the fundamental differences between the two forms of supply. As a consequence the efficient use of renewable energy requires the correct application of certain principles.

1.4.1 Energy currents

It is essential that a sufficient renewable current is *already present* in the local environment. It is not good practice to try to create this energy current especially for a particular system. Renewable energy was once ridiculed by calculating the number of pigs required to produce dung for sufficient methane generation to power a whole city. It is obvious, however, that biogas (methane) production should only be contemplated as a *by-product* of an animal industry already established, and not vice versa. Likewise for a biomass energy station, the biomass resource must exist locally to avoid large inefficiencies in transportation. The practical implication of this principle is that the local environment has to be monitored and analysed over a long period to establish precisely what energy flows are present. In Figure 1.1 the energy current ABC must be assessed before the diverted flow through DEF is established.

1.4.2 Dynamic characteristics

End-use requirements for energy vary with time. For example, electricity demand on a power network often peaks in the morning and evening, and reaches a minimum through the night. If power is provided from a finite source, such as oil, the input can be adjusted in response to demand. Unused energy is not wasted, but remains with the source fuel. However, with renewable energy systems, not only does end-use vary uncontrollably with time but so too does the natural supply in the environment. Thus a renewable energy device must be matched dynamically at both D and E of Figure 1.1; the characteristics will probably be quite different at both interfaces. Examples of these dynamic effects will appear in most of the following chapters.

The major periodic variations of renewable sources are listed in Table 1.2, but precise dynamic behaviour may well be greatly affected by irregularities. Systems range from the very variable (e.g. wind power) to the accurately predictable (e.g. tidal power). Solar energy may be very predicable in some regions (e.g. Khartoum) but somewhat random in others (e.g. Glasgow).

1.4.3 Quality of supply

The quality of an energy supply or store is often discussed, but usually remains undefined. We define *quality* as the proportion of an energy source that can be converted to mechanical work. Thus electricity has high quality because when consumed in an electric motor >95% of the input energy may be converted to mechanical work, say to lift a weight; the heat losses are correspondingly small, <5%. The quality of nuclear, fossil or biomass fuel in a single stage thermal power station is moderately low, because only about 33% of the calorific value of the fuel can be made to appear as mechanical work and about 67% is lost as heat to the environment. If the fuel is used in a combined cycle power station (e.g. methane gas turbine stage followed by steam turbine), then the quality is increased to ~50%. It is possible to analyse such factors in terms of the thermodynamic variable energy, defined here as 'the theoretical maximum amount of work obtainable, at a particular environmental temperature, from an energy source'.

Table 1.2 Intensity and periodical properties of renewable sources

System	*Major periods*	*Major variables*	*Power relationship*	*Comment*	*Text reference (equation)*
Direct sunshine	24 h, 1 y	Solar beam irradiance $G_b^*(\mathrm{W\,m^{-2}})$; Angle of beam from vertical θ_z	$P \propto G_b^* \cos\theta_z$ $P_{max} = 1\,\mathrm{kW\,m^{-2}}$	Daytime only	(4.2)
Diffuse sunshine	24 h, 1 y	Cloud cover, perhaps air pollution	$P \ll G$; $P \leq 300\,\mathrm{W\,m^{-2}}$	Significant energy over time	(4.3)
Biofuels	1 y	Soil condition, insolation, water, plant species, wastes	Stored energy $\sim 10\,\mathrm{MJ\,kg^{-1}}$	Very many chemical types and sources. Linked to agriculture and forestry. Stored energy	Table 11.1 Table 11.4
Wind	1 y	Wind speed u_0 Height nacelle above ground z; height of anemometer mast h	$P \propto u_0^3$ $u_z/u_h = (z/h)^b$	Most variable $b \sim 0.15$	(9.2) (9.54)
Wave	1 y	'Significant wave height' H_s wave period T	$P \propto H_s^2 T$	Relatively large power density $\sim 50\,\mathrm{kW\,m^{-1}}$ across wave front	(12.47)
Hydro	1 y	Reservoir height H water volume flow rate Q	$P \propto HQ$	Established resource	(8.1)
Tidal	12 h 25 min	Tidal range R; contained area A; estuary length L, depth h	$P \propto R^2 A$	Enhanced tidal range if $L/\sqrt{h} = 36\,000\,\mathrm{m^{1/2}}$	(13.35) and (13.28)
		Tidal stream/current; peak current u_0, density sea water $\rho(\sim 1000 \times \text{air})$	$P \propto \rho u_0^3$	Enhanced tidal currents between certain islands	(13.30)
Ocean thermal energy conversion	Constant	Temperature difference between sea surface and deep water, ΔT	$P \propto (\Delta T)^2$	Some tropical locations have $\Delta T \sim 20\,°\mathrm{C}$, so potentially harnessable, but small efficiency	(14.5)

Renewable energy supply systems divide into three broad divisions:

1 *Mechanical supplies*, such as hydro, wind, wave and tidal power. The mechanical source of power is usually transformed into electricity at high efficiency. The proportion of power in the environment extracted by the devices is determined by the mechanics of the process, linked to the variability of the source, as explained in later chapters. The proportions are, commonly, wind 35%, hydro 70–90%, wave 50% and tidal 75%.
2 *Heat supplies*, such as biomass combustion and solar collectors. These sources provide heat at high efficiency. However, the maximum proportion of heat energy extractable as mechanical work, and hence electricity, is given by the second law of thermodynamics and the Carnot Theorem, which assumes reversible, infinitely long transformations. In practice, maximum mechanical power produced in a dynamic process is about half that predicted by the Carnot criteria. For thermal boiler heat engines, maximum realisable quality is about 35%.
3 *Photon processes*, such as photosynthesis and photochemistry (Chapter 10) and photovoltaic conversion (Chapter 7). For example, solar photons of a single frequency may be transformed into mechanical work via electricity with high efficiency using a matched solar cell. In practice, the broad band of frequencies in the solar spectrum makes matching difficult and photon conversion efficiencies of 20–30% are considered good.

1.4.4 Dispersed versus centralised energy

A pronounced difference between renewable and finite energy supplies is the energy flux density at the initial transformation. Renewable energy commonly arrives at about $1\,\text{kW}\,\text{m}^{-2}$ (e.g. solar beam irradiance, energy in the wind at $10\,\text{m}\,\text{s}^{-1}$), whereas finite centralised sources have energy flux densities that are orders of magnitude greater. For instance, boiler tubes in gas furnaces easily transfer $100\,\text{kW}\,\text{m}^{-2}$, and in a nuclear reactor the first wall heat exchanger must transmit several $\text{MW}\,\text{m}^{-2}$. At end-use after distribution, however, supplies from finite sources must be greatly reduced in flux density. Thus apart from major exceptions such as metal refining, end-use loads for both renewable and finite supplies are similar. In summary *finite energy is most easily produced centrally and is expensive to distribute. Renewable energy is most easily produced in dispersed locations and is expensive to concentrate*. With an electrical grid, the renewable generators are said to be 'embedded' within the (dispersed) system.

A practical consequence of renewable energy application is development and increased cash flow in the *rural* economy. Thus the use of renewable energy favours rural development and not urbanisation.

1.4.5 Complex systems

Renewable energy supplies are intimately linked to the natural environment, which is not the preserve of just one academic discipline such as physics or electrical engineering. Frequently it is necessary to cross disciplinary boundaries from as far apart as, say, plant physiology to electronic control engineering. An example is the energy planning of integrated farming (Section 11.8.1). Animal and plant wastes may be used to generate methane, liquid and solid fuels, and the whole system integrated with fertilizer production and nutrient cycling for optimum agricultural yields.

1.4.6 Situation dependence

No single renewable energy system is universally applicable, since the ability of the local environment to supply the energy and the suitability of society to accept the energy vary greatly. It is as necessary to 'prospect' the environment for renewable energy as it is to prospect geological formations for oil. It is also necessary to conduct energy surveys of the domestic, agricultural and industrial needs of the local community. Particular end-use needs and local renewable energy supplies can then be matched, subject to economic and environmental constraints. In this respect renewable energy is similar to agriculture. Particular environments and soils are suitable for some crops and not others, and the market pull for selling the produce will depend on particular needs. The main consequence of this 'situation dependence' of renewable energy is the impossibility of making simplistic international or national energy plans. Solar energy systems in southern Italy should be quite different from those in Belgium or indeed in northern Italy. Corn alcohol fuels might be suitable for farmers in Missouri but not in New England. A suitable scale for renewable energy planning might be 250 km, but certainly not 2500 km. Unfortunately present-day large urban and industrialised societies are not well suited for such flexibility and variation.

1.5 Technical implications

1.5.1 Prospecting the environment

Normally, monitoring is needed for several years at the site in question. Ongoing analysis must insure that useful data are being recorded, particularly with respect to dynamic characteristics of the energy systems planned. Meteorological data are always important, but unfortunately the sites of official stations are often different from the energy generating sites, and the methods of recording and analysis are not ideal for energy prospecting. However, an important use of the long-term data from official monitoring stations is as a base for comparison with local site variations. Thus wind velocity may be monitored for several months at a prospective generating site and compared with data from the nearest official base station. Extrapolation using many years of base station data may then be possible. Data unrelated to normal meteorological measurements may be difficult to obtain. In particular, flows of biomass and waste materials will often not have been previously assessed, and will not have been considered for energy generation. In general, prospecting for supplies of renewable energy requires specialised methods and equipment that demand significant resources of finance and manpower. Fortunately the links with meteorology, agriculture and marine science give rise to much basic information.

1.5.2 End-use requirements and efficiency

As explained in Section 1.3.5, energy generation should always follow quantitative and comprehensive assessment of energy end-use requirements. Since no energy supply is cheap or occurs without some form of environmental disruption, it is also important to use the energy efficiently with good methods of energy conservation. With electrical systems, the end-use requirement is called the *load*, and the size and dynamic characteristics of the load will greatly affect the type of generating supply. Money spent on energy conservation and improvements in end-use efficiency usually gives better long-term benefit than money spent on increased generation and supply capacity. The largest energy requirements are usually for heat and transport. Both uses are associated with energy storage capacity in thermal mass, batteries or fuel tanks, and the inclusion of these uses in energy systems can greatly improve overall efficiency.

1.5.3 Matching supply and demand

After quantification and analysis of the separate dynamic characteristics of end-use demands and environmental supply options, the total demand and supply have to be brought together. This may be explained as follows:

1 The maximum amount of environmental energy must be utilised within the capability of the renewable energy devices and systems. In Figure 1.4(a), the resistance to energy flow at D, E and F should be small. The main benefit of this is to reduce the size and amount of generating equipment.
2 *Negative feedback* control from demand to supply is *not* beneficial since the result is to waste or spill harnessable energy (Figure 1.4(b)); in effect the capital value of the equipment is not fully utilised. Such control should only be used at times of emergency or when all conceivable end-uses have been satisfied. Note that the disadvantage of negative feedback control is a consequence of *renewable* energy being flow or

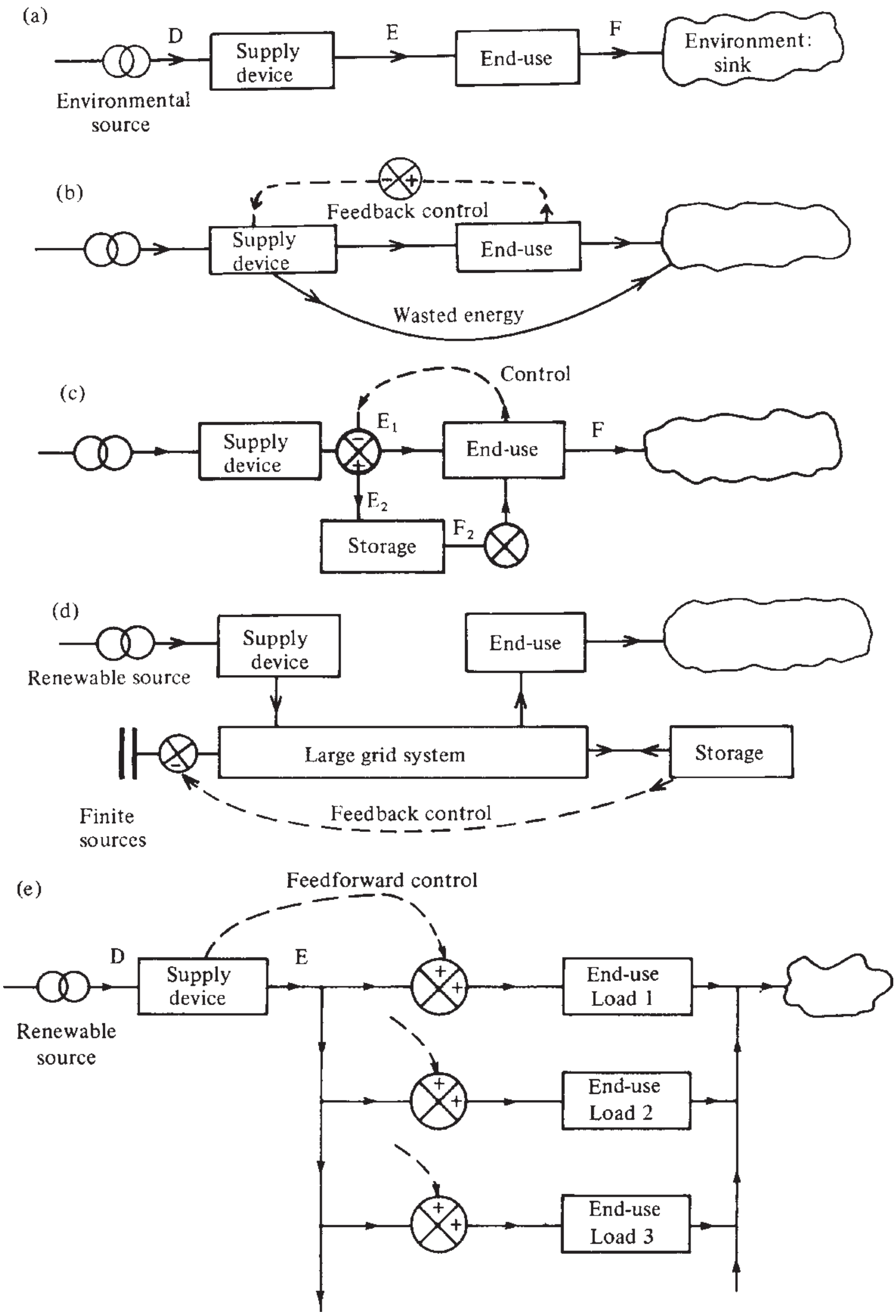

Figure 1.4 Matching renewable energy supply to end-use. (a) Maximum energy flow for minimum size of device or system requires low resistance to flow at D, E and F. (b) Negative feedback control wastes energy opportunity and capital value. (c) Energy storage allows the dynamic characteristics of end-use to be decoupled from the supply characteristics. (d) Decoupling with a large grid system. (e) Feedforward load management control of the supply; arguably the most efficient way to use renewable energy. Total load at E may be matched to the available supply at D at all times and so control the supply device.

current sources that can never be stopped. With *finite* energy sources, negative feedback control to the energy source is beneficial, since less fuel is used.

3 The natural periods and dynamic properties of end-use are most unlikely to be the same as those of the renewable supply, as discussed in Section 1.4.2. The only way to match supply and demand that have different dynamic characteristics, and yet not to waste harnessable energy, is to incorporate storage (Figure 1.4(c)). Satisfactory energy storage is expensive (see Chapter 16), especially if not incorporated at the earliest stages of planning.

4 The difficulties of matching renewable energy supplies to end-use in stand-alone systems are so great that one common approach is to decouple supply from local demand by connection to an energy network or grid (Figure 1.4(d)). Here the renewable supply is embedded in an energy grid network having input from finite sources having feedback control. Such systems imply relatively large scale operation and include electricity grids for transmission and distribution. As in (3) the addition of substantial energy storage in the system, say pumped hydro or thermal capacity for heating, can improve efficiency and allow the proportion of renewable supply to increase. By using the grid for both the export and the import of energy, the grid becomes a 'virtual store'.

5 The most efficient way to use renewable energy is shown in Figure 1.4(e). Here a range of end-uses is available and can be switched or adjusted so that the total load equals the supply at any one time. Some of the end-use blocks could themselves be adjustable (e.g. variable voltage water heating, pumped water storage). Such systems require *feedforward control* (see Section 1.5.4). Since the end-use load increases with increase in the renewable energy supply, this is *positive feedforward control.*

1.5.4 Control options

Good matching of renewable energy supply to end-use demand is accomplished by control of machines, devices and systems. The discussion in Section 1.5.3 shows that there are three possible categories of control: (1) spill the excess energy, (2) incorporate storage and (3) operate load management control. These categories may be applied in different ways, separately or together, to all renewable energy systems, and will be illustrated here with a few examples (Figure 1.5).

1 *Spill excess energy.* Since renewable energy derives from energy flow sources, energy not used is energy wasted. Nevertheless spilling excess

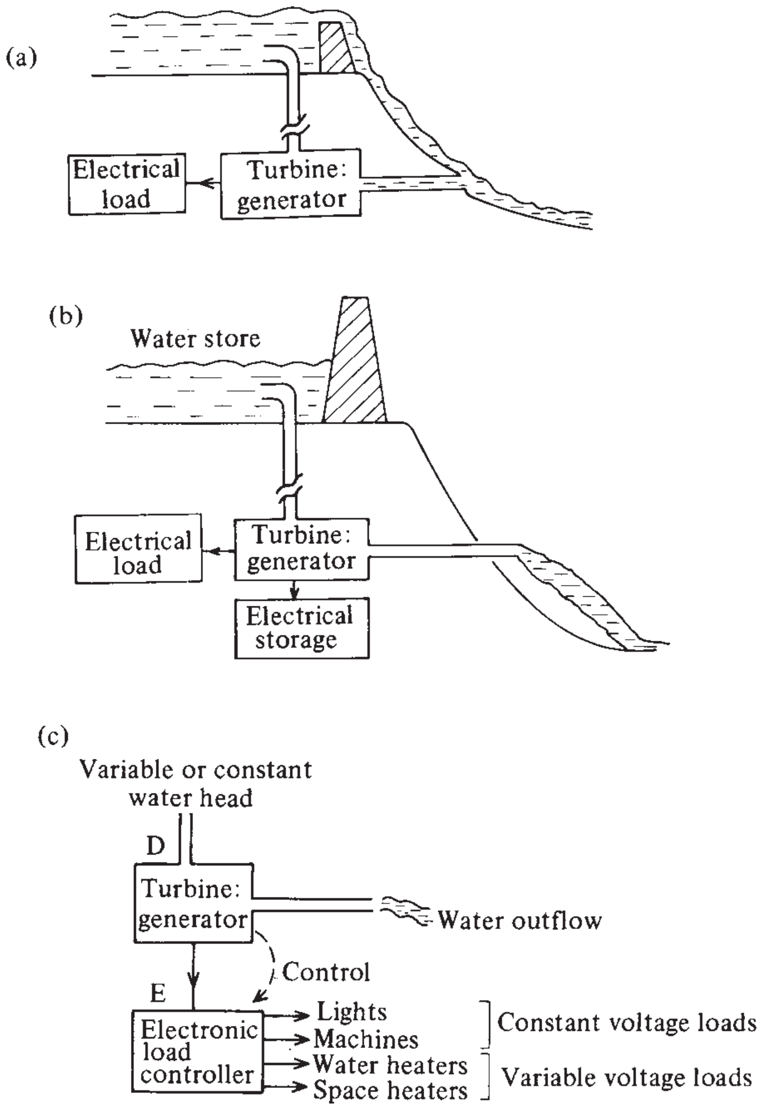

Figure 1.5 Examples of control. (a) Control by spilling excess energy: constant pressure maintained for the turbine. (b) Control incorporating storage in hydroelectric catchment dam. (c) Control by load variation: feedforward control. Load controller automatically shunts power between end-uses, maintaining constant generator load at E. Turbine also has constant load and hence constant frequency: only rudimentary mechanical control of turbine is needed.

energy provides easy control and may be the cheapest option. Examples occur with run-of-the-river hydroelectric systems (Figure 1.5(a)), shades and blinds with passive solar heating of buildings, and wind turbines with adjustable blade pitch.

2 *Incorporate storage.* Storage before transformation allows a maximum amount of energy to be trapped from the environment and eventually

harnessed or used. Control methods are then similar to conventional methods with finite sources, with the store equivalent to fuel. The main disadvantages are the large relative capital costs of storage, and the difficulty of reducing conventional control methods to small-scale and remote operation. In the example of Figure 1.5(b), hydro storage is usually only contemplated for generation at more than ~10 MW. The mechanical flow control devices become unwieldy and expensive at a microhydro scale of ~10 kW. A disadvantage of hydro storage may be the environmental damage caused by reservoirs.

Storage after energy transformation, e.g. battery charging or hydrogen production, is also possible and may become increasingly important especially in small systems. Thermal storage is already common.

3 *Load control.* Parallel arrangements of end-uses may be switched and controlled so as to present optimum total load to the supply. An example of a microhydro load controller for household power is shown in Figure 1.5(c) (see also Section 8.6). The principle may be applied on a small or large scale, but is perhaps most advantageous when many varied end-uses are available locally. There are considerable advantages if load control is applied to renewable energy systems:

a No environmental energy need be wasted if parallel outputs are opened and closed to take whatever input energy flow is available. Likewise, the capital-intensive equipment is well used.
b Priorities and requirements for different types of end-use can be incorporated in many varied control modes (e.g. low priority uses can receive energy at low cost, provided that they can be switched off by feedforward control; electrical resistive heaters may receive variable voltage and hence variable power).
c End-uses having storage capability (e.g. thermal capacity of water heating and building space conditioning) can be switched to give the benefits of storage in the system at no extra cost.
d Electronic and microprocessor-based control may be used with benefits of low cost, reliability, and extremely fast and accurate operation.

Feedforward load control may be particularly advantageous for autonomous wind energy systems (see Chapter 9, especially Section 9.8.2). Wind fluctuates greatly in speed and the wind turbine should change rotational frequency to maintain optimum output. Rapid accurate control is necessary without adding greatly to the cost or mechanical complexity, and so electronically based feedforward control into several parallel electrical loads is most useful. An example is shown in Figure 1.6.

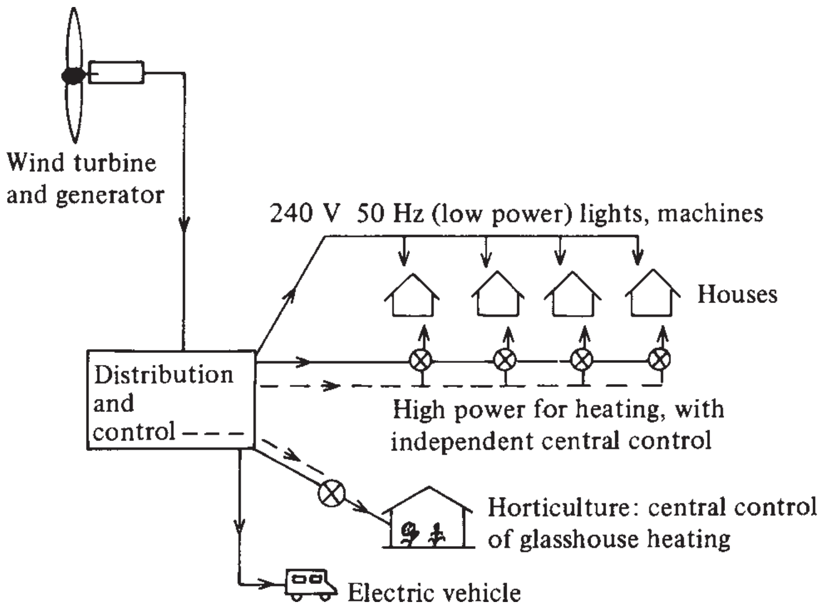

Figure 1.6 Wind energy conversion system for Fair Isle, Scotland. Electrical loads are switched by small changes in the supply frequency, so presenting a matched load to the generator over a wide range of wind speeds.

1.6 Social implications

The Industrial Revolution in Europe and North America and industrial development in all countries have profoundly affected social structures and patterns of living. The influence of changing and new energy sources has been the driving function for much of this change. Thus there is a historic relationship between coal mining and the development of industrialised countries, which will continue for several hundred years. In the non-industrialised countries, relatively cheap oil supplies became available in the 1950s at the same time as many countries obtained independence from colonialism. Thus in all countries the use of fossil fuels has led to profound changes in lifestyle.

1.6.1 Dispersed living

In Sections 1.1 and 1.4.4 the dispersed and small energy flux density of renewable sources was discussed. Renewable energy arrives dispersed in the environment and is difficult and expensive to concentrate. By contrast finite energy sources are energy stores that are easily concentrated at source and expensive to disperse. Thus electrical distribution grids from fossil fuel and nuclear sources tended to radiate from central, intensive distribution points, typically with $\sim$1000 MW_e capacity. Industry has developed on these grids, with heavy industry closest to the points of intensive supply. Domestic populations have grown in response to the employment opportunities of industry and commerce. Similar effects have occurred with the relationships between coal mining and steel production, oil refining and chemical engineering and the availability of gas supplies and urban complexes.

This physical review of the effect of the primary flux density of energy sources suggests that widespread application of renewable energy will favour dispersed, rather than concentrated, communities. Electricity grids in such situations are powered by smaller-scale, embedded, generation, with power flows moving intermittently in both directions according to local generation and local demand. In Section 1.2.2 an approximate estimate of 500 people per square kilometre was made of maximum population density for communities relying on renewable sources. This is considerably greater than for rural communities (~100 people per square kilometre) and corresponds with the population densities of the main administration and commercial towns of rural regions. Thus the gradual acceptance of significant supplies of renewable energy could allow relief from the concentrated metropolises of excessive urbanisation, yet would not require unacceptably low population densities. A further advantage is the increased security for a nation having its energy supplies from such indigenous and dispersed sources.

1.6.2 Pollution and environmental impact

Harmful emissions can be classified as chemical (as from fossil fuel and nuclear power plant), physical (including acoustic noise and radioactivity) and biological (including pathogens); such pollution from energy generation is overwhelmingly a result of using ‘brown’ fuels, fossil and nuclear. In contrast, renewable energy is always extracted from flows of energy already compatible with the environment (Figure 1.1). The energy is then returned to the environment, so no thermal pollution can occur on anything but a small scale. Likewise material and chemical pollution in air, water and refuse tend to be minimal. An exception is air pollution from incomplete combustion of biomass or refuses (see Chapter 11). Environmental pollution does occur if brown energy is used for the materials and manufacture of renewable energy devices, but this is small over the lifetime of the equipment.

The environmental impact of renewables depends on the particular technology and circumstances. We consider these in the last section of each technology chapter that follows. General institutional factors, often related to the abatement of pollution, are considered in the last chapter.

1.6.3 The future

In short, we see that many changes in social patterns are related to energy supplies. We can expect further changes to occur as renewable energy systems become widespread. The influence of modern science and technology ensures that there are considerable improvements to older technologies, and subsequently standards of living can be expected to rise, especially in rural and previously less developed sectors. It is impossible to predict exactly the long-term effect of such changes in energy supply, but the sustainable nature of renewable energy should produce greater socio-economic stability than has been the case with fossil fuels and nuclear power. In particular we expect the great diversity of renewable energy supplies to be associated with a similar diversity in local economic and social characteristics.

Problems

1.1 a Show that the average solar irradiance absorbed during 24 h over the whole Earth's surface is about 230 W (see Figure 1.2)

b Using devices, the average local power accessible can be increased, e.g. by tilting solar devices towards the Sun, by intercepting winds. Is it reasonable to state that 'each square metre of the Earth's *habitable* surface is crossed or accessible to an average flux of about 500 W'?

1.2 a Compare the direct costs to the consumer of using:

i a succession of ten 100 W incandescent light bulbs with an efficiency for electricity to visible light of 5%, life of 1 000 h, price €0.5;

ii one compact fluorescent lamp (CFL) giving the same illumination at 22% efficiency, life of 10 000 h, price €3.0. Use a fixed electricity price of €0.10 kW h^{-1};

b what is the approximate payback time in lighting-hours of (b) against (a). [See also Problem 17.1 that allows for the more sophisticated discounted costs.]

1.3 Repeat the calculation of Problem 1.2, with tariff prices of your local lamps and electricity. Both the price of CFL's in local shops and of electricity vary markedly, so your answers may differ significantly. Nevertheless it is highly likely the significant lifetime savings will still occur.

1.4 Economists argue that as oil reserves become smaller, the price will increase, so demand will decrease and previously uneconomic supplies will come into production. This tends to make the resource last longer than would be suggested by a simple calculation (based on 'today's reserves' divided by 'today's use') . On the other hand, demand increases driven by increased economic development in developing countries tend to shorten the life of the reserve. Discuss.

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Refer to the bibliographies at the end of each chapter for particular subjects and technologies.

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World Commission on Environment and Development (1987) *Our Common Future*, Oxford University Press (the 'Bruntland report'). {A seminal work, warning about the key issues in plain language for politicians.}

Official publications (including energy statistics and projections)

See also below under journals and websites, as many official publications, especially those of a statistical nature, are updated every year or two. United Nations agencies produce a wide range of essential publications regarding energy. These are especially important for data. For instance we recommend:

United Nations *World Energy Supplies*, UN document no. ST/ESA/STAT/SER.J/l9, annual. Gives statistics of energy consumption around the world, classified by source, country, continent, etc., but counts only 'commercial energy' (i.e. excludes firewood, etc.).

Government publications are always important. For instance, UK Department of Energy Series of Energy Papers. Such publications are usually clearly written and include economic factors at the time of writing. Basic principles are covered, but usually without the details required for serious study. Annual updates of many of government and UN publications are also available through the corresponding websites.

World Energy Council (2001) *Survey of world energy resources*. {Compiled every 5 years or so by the WEC, which comprises mainly energy utility companies from around the world; covers both renewable and non-renewable resources.}

International Energy Agency, *World Energy Outlook* (annual), Paris. {Focus is on fossil fuel resources and use, based on detailed projections for each member country, and for those non-member countries which are significant in world energy markets, e.g. OPEC and China.}

Do-it-yourself publications

There are many publications for the general public and for enthusiasts. Do not despise these, but take care if the tasks are made to look easy. Many of these publications give stimulating ideas and are attractive to read, e.g. Merrill, R. and Gage, T. (eds) *Energy Primer*, Dell, New York (several editions).

Berrill, T. *et al.* (eds) (2003, 4th edn) *Introduction to Renewable Energy Technologies: Resource book*, Australian Centre for Renewable Energy, Perth. {Written with tradespeople in mind; clearly describes available equipment with basic account of principles; emphasis on practicalities of installation and operation.}

Journals, trade indexes and websites

Renewable energy and more generally energy technology and policy are continually advancing. Use a web search engine for general information and for technical explanations and surveys. For serious study it is necessary to refer to the periodical literature (journals and magazines), which is increasingly available on the web, with much more available by payment. Websites of key organisations, such as those listed below and including governmental sites with statistical surveys, also carry updates of our information.

We urge readers to scan the serious scientific and engineering journals, e.g. *New Scientist*, *Annual Review of Energy and the Environment*, and magazines, e.g. *Electrical Review*, *Modern Power Systems*. These publications regularly cover renewable energy projects among the general articles. The magazine *Refocus*, published for the International Solar Energy Society, carries numerous well-illustrated articles on all aspects of renewable energy. The series *Advances in Solar Energy*, published by the American Solar Energy Society, comprises annual volumes of high level reviews, including all solar technologies and some solar-derived technologies (e.g. wind power and biomass). There are also many specialist journals, such as *Renewable and Sustainable Energy Reviews*, *Solar Energy*, *Wind Engineering*, and *Biomass and Bioenergy*, referred to in the relevant chapters.

As renewable energy has developed commercially, many indexes of companies and products have been produced; most are updated annually, e.g. *European Directory of Renewable Energy Supplies and Services*, annual, ed. B. Cross, James and James, London.

www.iea.org
The International Energy Agency (IEA) comprises the governments of about 20 industrialised countries; its publications cover policies, energy statistics and trends, and to a lesser extent technologies; it also co-ordinates and publishes much collaborative international R&D, including clearly written appraisals of the state of the art of numerous renewable energy technologies. Its publications draw on detailed inputs from member countries.

www.wec.org
The World Energy Council comprises mainly energy utility companies for around the world, who cooperate to produce surveys and projections of resources, technologies and prices.

www.ipcc.ch
The Intergovernmental Panel on Climate Change (IPCC) is a panel of some 2000 scientists convened by the United Nations to report on the science, economics and mitigation of greenhouse gases and climate change; their reports, issued every five years or so, are regarded as authoritative. Summaries are available on the website.

www.itdg.org
ITDG (the Intermediate Technology Development Group) develops and promotes simple and cheap but effective technology – including renewable energy technologies – for use in rural areas of developing countries. They have an extensive publication list plus on-line 'technical briefs'.

www.caddet.org
The acronym CADDET stands for Centre for the Analysis and Dissemination of *Demonstrated* Energy Technologies. The site gives information and contact details about renewable energy and energy efficiency projects from many countries.

www.ewea.org
European Wind Energy Association is one of many renewable energy associations, all of which have useful websites. Most such associations are 'trade associations', as funded by members in the named renewable energy industry. However, they are aware of the public and educational interest, so will have information and give connections for specialist information.