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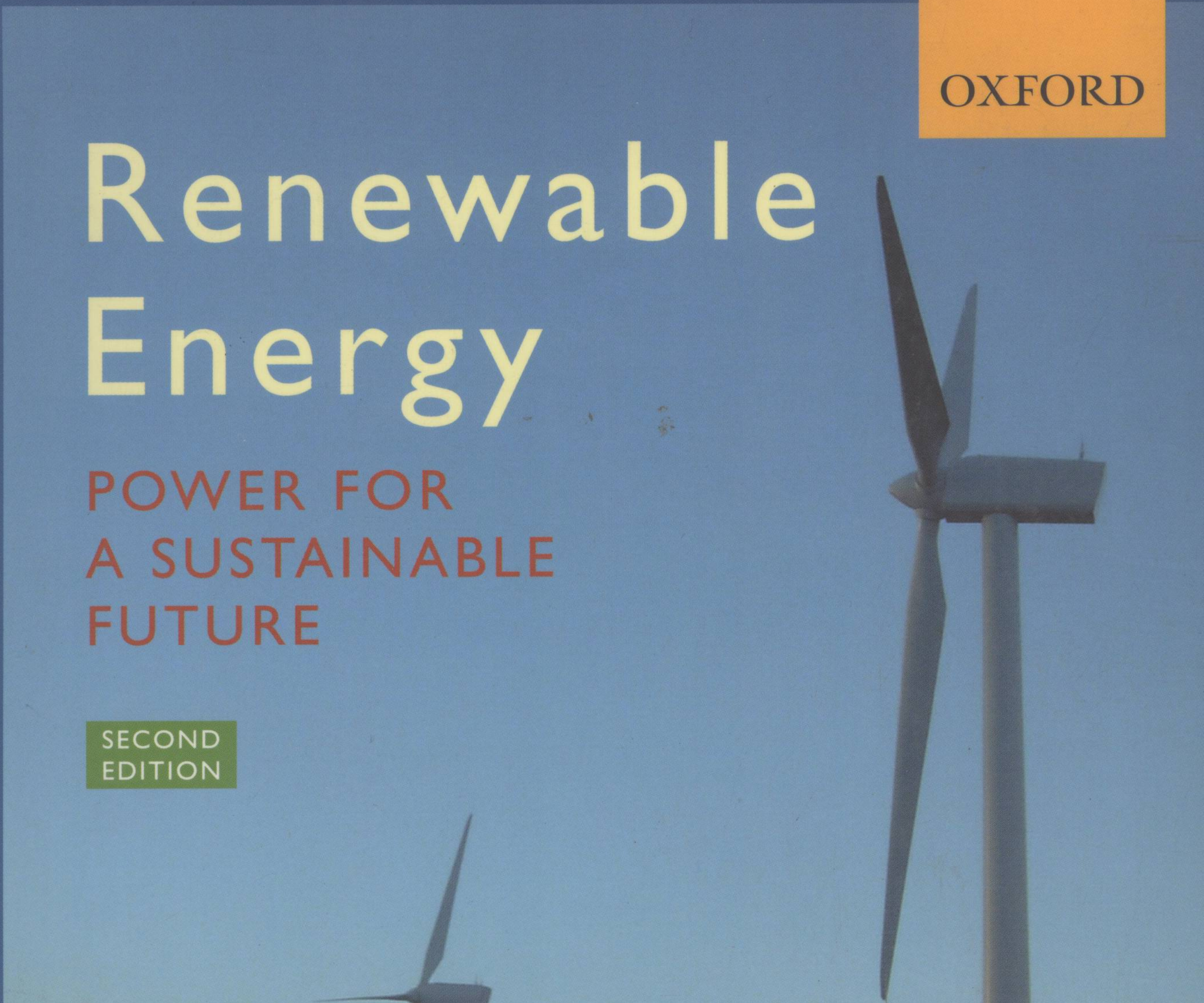


Renewable Energy

POWER FOR A SUSTAINABLE FUTURE

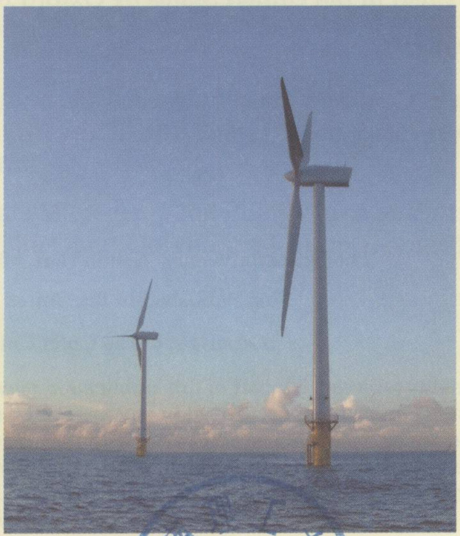
SECOND EDITION

EDITED BY

Godfrey Boyle

Renewable Energy

Edited by Godfrey Boyle



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T206 Energy for a Sustainable Future is also accompanied by two other textbooks, a set of Study Guides and a variety of other supplementary printed materials. This additional course material also includes several hours of material on video, produced by the BBC in partnership with the Open University, and a number of software-based exercises and simulations on CD-ROM. A selection of these are available from the Open University Worldwide Learning Resources webshop at www.ouw.co.uk/ or by writing to Open University Worldwide, Walton Hall, Milton Keynes, MK7 6AA.

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Preface to the Second Edition

By the end of the twenty-first century, if current trends continue, the world's population is likely to have almost doubled and its wealth increased by a factor of between eight and sixteen times. World energy demand will probably have doubled and possibly quadrupled, despite major improvements in energy efficiency. How can this enormous demand be supplied, cleanly, safely and sustainably?

Even at current consumption levels, existing energy systems have many deleterious effects on human health and the natural environment, as described in our companion text *Energy Systems and Sustainability: Power for a Sustainable Future*. In particular, carbon dioxide and other greenhouse gases released by fossil fuel burning threaten to cause unprecedented changes in the earth's climate, with mainly adverse consequences. There is now a broad consensus that in the long term the world will need to shift to low- or zero-carbon energy sources if the impacts of climate change are to be mitigated.

The renewable energy sources are essentially carbon-free and appear to be generally more sustainable than fossil or nuclear fuels, though many technologies are still under development and the costs of some are currently high. This new edition of *Renewable Energy* reflects the remarkable progress that has been made in the field since the publication of the first edition in 1996. With that progress has come greatly increased recognition among professionals, politicians and the public that renewable energy could provide a major proportion of the world's needs by the middle of the twenty-first century, given adequate investment in research, development and deployment.

But if that potential is to be realised, the world will need many more professional people with a thorough knowledge of renewable energy systems, their underlying physical and technological principles, their economics, their environmental impact and how they can be integrated into the world's energy systems.

This book and its companion text aim to address these needs. Written initially for undergraduates studying the course T206 *Energy for a Sustainable Future* at the Open University, they are also aimed at students and staff in other universities, and at professionals, policy-makers and members of the public interested in sustainable energy futures. We hope that both books will contribute to an improved understanding of the sustainability problems of our present energy systems and of potential solutions. We also hope they convey something of the enthusiasm we feel for this complex, fascinating and increasingly important subject.

Godfrey Boyle
Course Team Chair, T206 *Energy for a Sustainable Future*

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Chapter 1

Introducing Renewable Energy

by Gary Alexander and Godfrey Boyle

1.1 Introduction

The renewable energy sources, derived principally from the enormous power of the sun's radiation, are at once the most ancient and the most modern forms of energy used by humanity.

Solar power, both in the form of direct solar radiation and in indirect forms such as bioenergy, water or wind power, was the energy source upon which early human societies were based. When our ancestors first used fire, they were harnessing the power of photosynthesis, the solar-driven process by which plants are created from water and atmospheric carbon dioxide. Societies went on to develop ways of harnessing the movements of water and wind, both caused by solar heating of the oceans and atmosphere, to grind corn, irrigate crops and propel ships. As civilizations became more sophisticated, architects began to design buildings to take advantage of the sun's energy by enhancing their natural use of its heat and light, so reducing the need for artificial sources of warmth and illumination.

Technologies for harnessing the powers of sun, firewood, water and wind continued to improve right up to the early years of the industrial revolution. But by then the advantages of coal, the first and most plentiful of the fossil fuels had become apparent. These highly-concentrated energy sources soon displaced wood, wind and water in the homes, industries and transport systems of the industrial nations. Today the fossil fuel trio of coal, oil and natural gas provides three quarters of the world's energy.

Concerns about the adverse environmental and social consequences of fossil fuel use, such as air pollution or mining accidents, and about the finite nature of supplies, have been voiced intermittently for several centuries. But it was not until the 1970s, with the steep price rises of the 'oil crisis' and the advent of the environmental movement, that humanity began to take seriously the possibility of fossil fuels 'running out', and that their continued use could be destabilizing the planet's natural ecosystems and the global climate (see Section 3 below).

The development of nuclear energy following World War II raised hopes of a cheap, plentiful and clean alternative to fossil fuels. But nuclear power development has stalled in recent years, due to increasing concern about cost, safety, waste disposal and weapons proliferation.

Continuing concerns about the 'sustainability' of both fossil and nuclear fuels use have been a major catalyst of renewed interest in the renewable energy sources in recent decades. Ideally, a **sustainable energy source** is one that is not substantially depleted by continued use, does not entail significant pollutant emissions or other environmental problems, and does not involve the perpetuation of substantial health hazards or social injustices. In practice, only a few energy sources come close to this ideal, but as this and subsequent chapters will show, the 'renewables' appear generally more sustainable than fossil or nuclear fuels: they are essentially inexhaustible and their use usually entails much lower emissions of greenhouse gases or other pollutants, and fewer health hazards.

Before going on to introduce the renewables in more detail, let us now pause to introduce some basic energy concepts that may be unfamiliar to readers who do not have a scientific background. For a more detailed discussion, see the companion text *Energy Systems and Sustainability* (Boyle *et al*, 2003).

Force, energy and power

The word energy is derived from the Greek *en* (in) and *ergon* (work). The scientific concept of **energy** serves to reveal the common features in processes as diverse as burning fuels, propelling machines or charging batteries. These and other processes can be described in terms of diverse **forms of energy**, such as *thermal* energy (heat), *chemical* energy (in fuels or batteries), *kinetic* energy (in moving substances), *electrical* energy, *gravitational* potential energy, and various others.

BOX 1.1 The SI system of units

In 1960, the scientific world agreed on a single set of units: the SI system (Système Internationale d'Unités). There are three basic units: the *metre* (m), the *kilogram* (kg) and the *second* (s); the units for many other quantities are derived from these. For some of the derived units, such as *metres per second* ($m\ s^{-1}$), the unit for speed, the base units are obvious. Others have been given specific names – such as the newton, or the joule. (See Appendix A2 for more details.)

To change the motion of any object, a **force** is needed, and the formal **SI unit** (see Box 1.1) for force, the **newton** (N), is defined as that force which will accelerate a mass of one kilogram (kg) at a rate of one metre per second per second ($m\ s^{-2}$). More generally,

$$\text{Force (N)} = \text{mass (kg)} \times \text{acceleration (m s}^{-2}\text{)}.$$

In the real world, force is often needed to move an object even at a steady speed, but this is because there are opposing forces such as friction to be overcome.

Whenever a force is moving something, it must be providing **energy**. The unit of energy, the **joule** (J), is defined as the energy supplied by a force of one newton in causing movement through a distance of 1 metre. In general:

$$\text{Energy (in joules)} = \text{Force (in newtons)} \times \text{Distance (in metres)}$$

The terms *energy* and *power* are often used informally as though they were synonymous (e.g. wind energy/wind power), but in scientific discussion it is important to distinguish them. **Power** is the *rate* at which energy is converted from one form to another, or transferred from one place to another. Its unit is the **watt** (W), and one watt is defined as one joule per second. A 100 watt light bulb, for example, is converting one hundred joules of electrical energy into light (and 'waste' heat) each second.

In practice, it is often convenient to measure energy in terms of power used for a given time period. If the power of an electric heater is 1 kW, and it runs for an hour, we say that it has consumed one **kilowatt-hour (kWh)** of energy. (Appendix A2 explains prefixes such as kilo-, mega-, etc.). A kilowatt is 1000 watts, i.e. 1000 joules per second, and there are 3600 seconds in an hour, so $1\ \text{kWh} = 3600 \times 1000 = 3.6 \times 10^6$ Joules (i.e. 3.6 MJ).

Energy is also often measured simply in terms of quantities of fuel, such as tonnes of coal or oil. National energy statistics often use the unit 'million tonnes of oil equivalent' (1 Mtoe = 41.9 PJ). The most common units and their conversion factors are listed in Appendix A2.

Energy conservation: The First Law of Thermodynamics

In any transformation of energy from one form to another, the total quantity of energy remains unchanged. This principle, that energy is always conserved, is called the **First Law of Thermodynamics**. So if the quantity of energy in the output of a power station, for example, is less than the quantity of energy in the fuel input, then some of the energy must have been converted to some other form (usually waste heat).

If the total quantity of energy is always the same, how can we talk of *consuming* it? Strictly speaking, we don't: we just convert it from one form into other forms. We consume fuels, which are sources of readily-available energy. We burn fuel in an engine, converting its stored chemical energy into heat and then into the kinetic energy of the moving vehicle. A wind turbine extracts kinetic energy from moving air and converts it into electrical energy, which can in turn be used to heat the filament of a lamp causing it to radiate light energy.

Forms of energy

At the most basic level, the diversity of energy forms can be reduced to four: *kinetic, gravitational, electrical* and *nuclear*.

The first of these is exemplified by the **kinetic energy** possessed by any moving object. This is equal to half the mass of the object times the square of its speed, i.e.:

$$\text{kinetic energy} = 0.5 \times \text{mass} \times \text{speed}^2$$

where energy is in joules (J), mass in kilograms (kg) and speed in metres per second (m s^{-1}).

Less obviously, kinetic energy *within* a material determines its temperature. All matter consists of atoms, or combinations of atoms called molecules. In a gas such as the air that surrounds us, these move freely. In a solid or a liquid, they form a more or less loosely linked network in which every particle is constantly vibrating. **Thermal energy**, or heat, is the name given to the kinetic energy associated with this rapid random motion. The higher the **temperature** of a body, the faster its molecules are moving. In the temperature scale that is most natural to scientific theory, the Kelvin (K) scale, zero corresponds to zero molecular motion. In the more commonly used Celsius scale of temperature (written as °C), zero corresponds to the freezing point of water and 100 to the boiling point of water. The two scales are related by a simple formula:

$$\text{temperature (K)} = \text{temperature (°C)} + 273.$$

A second fundamental form of energy is **gravitational energy**. On earth, an input of energy is required to lift an object because the gravitational pull of the earth opposes the movement. If an object such as an apple is lifted above your head, the input energy is stored in a form called **gravitational potential energy** (often just 'potential energy' or 'gravitational energy'). That this stored energy exists is obvious if you release the apple and observe the subsequent conversion to kinetic energy. The gravitational force pulling an object towards the earth is called the *weight* of the object, and is equal to its *mass*, m, multiplied by the acceleration due to gravity, g (which is 9.81 m s^{-2}). (Note that although everyday language may treat mass and weight as the same, science does not). The potential energy (in joules) stored in raising an object of mass m (in kilograms) to a height h (in metres) is given by the following equation

$$\text{potential energy} = \text{force} \times \text{distance} = \text{weight} \times \text{height} = m \times g \times h.$$

Gravity is not the only force influencing the objects around us. On a scale far too small for the eye to see, electrical forces hold together the atoms and molecules of all materials; gravity is an insignificant force at the molecular level. The **electrical energy** associated with these forces is the third of the basic forms. Every atom can be considered to consist of a cloud of electrically charged particles, electrons, moving incessantly around a central nucleus. When atoms come together to form molecules or solid materials, the distribution of electrons is changed, often with dramatic effect. Thus **chemical energy**, viewed at the atomic level, can be considered a form of electrical energy. When a fuel is burned, the chemical energy it contains is converted into heat energy. Essentially, the electrical energy released as the atomic electrons are rearranged is converted to the kinetic energy of the molecules of the combustion products.

A more familiar form of electrical energy is that carried by **electric currents** – organized flows of electrons in a material, most often a metal. In metals, one or two electrons from each atom can become detached and move freely through the lattice structure of the material. These 'free electrons' allow metals to carry electrical currents. To maintain a steady current of electrons requires a constant input of energy because the electrons continually lose energy in collisions with the metal lattice (which is why wires get hot when they carry electric currents). Voltage (in volts) is a measure of the energy required to maintain a current. The power (in watts) delivered by an electrical supply, or used by an appliance, is given by multiplying the voltage (in volts) by the current (measured in amperes, or 'amps'): i.e.

$$\text{power} = \text{voltage} \times \text{current}$$

In a typical power station, the input fuel is burned and used to produce high-pressure steam, which drives a rotating turbine. This in turn drives an electrical generator, which operates on a principle discovered by Michael Faraday in 1832: that a voltage is induced in a coil of wire set spinning in a magnetic field. Connecting the coil to an electric circuit will then allow a current to flow. The electrical energy can in turn be transformed into heat, light, motion or whatever, depending upon what is connected to the circuit. Electricity is thus a convenient *intermediary* form of energy: it allows energy released from one source to be converted to another quite different form, usually at some distance from the source.

Another form of electrical energy is that carried by electromagnetic radiation. More properly called **electromagnetic energy**, this is the form in which, for example, solar energy reaches the earth. Electromagnetic energy is radiated in greater or lesser amounts by every object. It travels as a wave that can carry energy through empty space. The length of the wave (its wavelength) characterizes its form, which includes X-rays, ultraviolet and infrared radiation, visible light, radio waves and microwaves.

The fourth and final basic form of energy, bound up in the central nuclei of atoms, is called **nuclear energy**. The technology for releasing it was developed during the Second World War for military purposes, and subsequently in a more controlled version for the peaceful production of electricity. Nuclear power stations operate on much the same principles as fossil fuel plants, except that the furnace in which the fuel burns is replaced by a nuclear reactor in which atoms of uranium are split apart in a 'fission' process that generates large amounts of heat.

The energy source of the sun is also of nuclear origin. Here the process is not nuclear fission but nuclear fusion, in which enormous quantities of hydrogen atoms fuse to form helium atoms, generating massive amounts of solar radiation in the process. Attempts to imitate the sun by creating power-producing nuclear fusion reactors have been the subject of many decades of research and development effort but have yet to come to fruition.

Conversion and efficiency

When we convert energy from one form to another, the useful output is never as much as the input. The ratio of the useful output to the required input (usually expressed as a percentage) is called the **efficiency** of the process. It can be as high as 90% in a water turbine or well-run electric motor, around 35–40% in a coal-fired power station (if the 'waste' heat is not put to use), and as low as 10–20% in a typical internal combustion engine. Some inefficiencies can be avoided by good design, but others are inherent in the nature of the type of energy conversion.

In the systems mentioned above, the difference between the high and low conversion efficiencies is because the latter involve the conversion of *heat* into mechanical or electrical energy. Heat, as we have seen, is the kinetic energy of randomly-moving molecules, an essentially chaotic form of energy. No machine can convert this chaos completely into the ordered state associated with mechanical or electrical energy. This is the essential message of the **Second Law of Thermodynamics**: that there is necessarily a limit to the efficiency of any heat engine. Some energy must always be rejected as low-temperature heat (This topic is discussed further in Box 2.4 of Chapter 2).

1.2 Present-day energy use

World energy supplies

World total annual consumption of all forms of **primary energy** increased more than ten-fold during the twentieth century, and in the year 2002 reached an estimated 451 EJ (exajoules), or some 10 800 Mtoe. As Figure 1.1 in Box 1.2 reveals, fossil fuels provided three quarters of the total. The world population in 2002 was some 6.2 billion, so the annual average energy consumption per person was about 74 GJ (gigajoules), equivalent to nearly 6 litres of oil per day for every man, woman and child.

But these figures conceal major differences. The average North American consumes nearly five times the world average: about 350 GJ per year. People in Europe and the former Soviet Union use about half this amount, and those in the rest of the world only about one fifth (see the companion text, Table 2.3).