Introduction

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Space, time and power are fundamentals of physics that determine the dynamic structure of our lives. Recent publications from the Darwin College Lecture Series have addressed two of these topics: *Space* in the 2001 lecture series and *Time* in 2000. Each of those volumes included a range of perspectives that span the arts, humanities and sciences. Now, in this new volume, we have invited seven international authorities to analyse and interpret the theme of *Power* as it is understood in their different fields of learning. The subjects that they consider include not only the sources of power that humanity has at its disposal, but also the forms of power that are exerted over us by cultural products and societies.

Life on earth, and of course all human activity, depends on the availability of sufficient power to support that activity. Mary Archer starts our exploration of power by considering where this power comes from. Drawing both on her academic work as a researcher in chemistry and Professor of Energy Policy, and on her public life including presidency of the National Energy Foundation, Archer reviews and forecasts human power usage and supply. Her chapter on the future of sustainable power sources addresses the rate with which we consume fossil fuel resources, and the alternatives that might supply the hundreds of exajoules we consume each year.

Grand topics of discussion require big numbers. An exajoule is 10 to the power of 18 – 1 000 000 000 000 000 000 or a billion billion – joules. In order to relate human experience to global phenomena, let alone the scale of our primary energy sources in the sun and other stars, we must use the language of mathematics. Neil deGrasse Tyson, director of the Hayden Planetarium in New York, gives us a tour of the power offered by this language, expressed

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as powers of ten, that extends our understanding of scale to the largest and smallest limits of the universe. John Conway, Professor of Mathematics at Princeton University, investigates the descriptive power of mathematics itself, beyond the structure of numbers and measurement, to the power that mathematical reasoning gives us to define, describe and predict the structures of our life.

The abstract mathematical world is becoming more real to us through the developments of digital technology. Digital technologies not only describe, but enhance and transform, our experience of the physical world, creating new universes of the imagination. Maureen Thomas, in the fourth chapter of this book, analyses the narrative power behind these universes. She surveys the history of narrative through the technologies that create new human experiences, from the two-dimensional screen of the moving image, to the development of three-dimensional camera motions that draw the viewer into and beyond the screen, and finally the fourth dimension of narrative control in interactive videogames. Elisabeth Bronfen then looks beyond narrative, to the whole range of literary devices that structure our aesthethic experience. Indeed Bronfen's chapter approaches the absolute limit of experience – the final and incommunicable experience of death. As she explains, the representation of death in art offers us a degree of power over its personal and social consequences.

Both Bronfen and Thomas draw our attention, through the insights of critical analysis, to the power that can be extended over an audience by artistic techniques. This power influences us all, whether or not we are aware of it. Even the abstract art of music, without any direct power of representation, becomes a channel for the expression of power. Music, however, is associated not only with power over our thoughts and emotions, but over whole societies. As Derek Scott demonstrates in his chapter on the power of music, even this abstract and non-representational art becomes a powerful medium for moral, behavioural and political persuasion.

Ultimately, the greatest concentration of power over our lives is the power exerted by our fellow men and women, through national and, increasingly, global politics. Tony Benn, one of our most experienced and respected parliamentarians, writes of the origins of power in society, the proper foundations of power for all peoples in the world and, as appropriate in a closing chapter, the opportunities we have to exert some power over our own futures.

It has been our privilege to work with these international leaders and thinkers, and we are grateful to Darwin College for having given us this opportunity. We are also grateful to Sally Thomas, Joseph Bottrill and Vincent Higgs at Cambridge University Press for their help in editing this collection from the Darwin Lecture Series, and to Themis Halvantzi for her valuable assistance with picture research.

1 Sustainable power

MARY ARCHER

Energy is vital to our economic and social well-being. Economic growth would be impossible without the ready availability of fuels to provide affordable heat, light and motive and electrical power. Yet the provision of power from fossil fuels poses a major threat to our environment, for we live, most of us now accept, in a globally warming world. Low-carbon technology will be essential in powering tomorrow's world in a sustainable way.

It has been said that extrapolation of the present North American per capita energy consumption to the world's population of 6 billion people would require the resources of several additional Earths to cope with the waste products, in particular the CO_2 (carbon dioxide) emissions that come from burning fossil fuels. Clearly that is unsustainable. Sustainable development, a concept popularised by the Brundlandt Report of 1987, is generally understood to mean development that enables us to meet our present needs without compromising the ability of future generations to meet their own needs. The UK government has been committed to sustainable development since 1994, and now monitors national progress in achieving sustainability in energy supply and consumption, as well as in other areas of life. 'National emissions of greenhouse gases' is one of the Department of Trade and Industry's (DTI's) six headline indicators of sustainability.

But would a sustainable energy policy pay for the sequestration of anthropogenic CO_2 emissions or for raising coastal defences to cope with rising sea levels? Would it encourage nuclear power on the grounds that it is CO_2-free or terminate it on account of the hazardous wastes it produces? Would it have us shivering in our thermal underwear in the dim light of one energy-efficient light bulb, or would it have us streaking around in hydrogen-fuelled cars in a

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world of abundant clean energy from solar or wind power? One's answer to these questions depends on the view one takes of the damage that global warming will do, the prospects of discovering significant new reserves of fossil fuels, the future pace of innovation in energy technology and technology transfer, the commercial prospects for renewables, and the political and economic risks involved in an expansion of nuclear power. In my view, sustainability in energy supply will best be achieved by maximising the future role of renewable energy, and thus I shall concentrate on technical innovation and the renewables in this chapter.

Current world energy consumption

To demonstrate the ways in which our current energy supply is unsustainable, I shall borrow an idea from the late Carl Sagan's book *The Dragons of Eden* and compress the long history of the world into one calendar year. On this time scale, 1 January represents the formation of the Earth by the condensation of interstellar matter some four and a half billion years ago, and it is now midnight on New Year's Eve. Life appeared on 9 February, 40 days after the formation of the Earth, and primitive photosynthetic organisms on 1 March. The Carboniferous Period, during which the Earth's deposits of coal, oil and gas were laid down by the decomposition of vegetable and animal matter, spanned the first fortnight of December.

On this time scale, quite a lot happens on New Year's Eve, as it tends to do in real life. *Homo sapiens sapiens*, presumably accompanied by *Femina sapienta sapienta*, emerged out of Africa 23 minutes ago. The Industrial Revolution, which marks the beginning of man's exploitation of the Earth's fossil fuel deposits, began just 1.5 seconds ago. Within the next few seconds – within the next few centuries in real time – most of the rest of this pre-packed solar energy will inevitably be consumed. We are midnight's children, striking one short hydrocarbon match in the middle of a long, dark night. When that hydrocarbon match burns low, assuming we have not by then discovered some new exploitable force of nature, we will have to turn to some combination of nuclear and renewable energy.

We may reach the same conclusion from Figure 1.1, which depicts the world's energy resources on a logarithmic scale. On the left are shown the energy contents of the world's proven reserves of oil, gas, coal and fissile uranium

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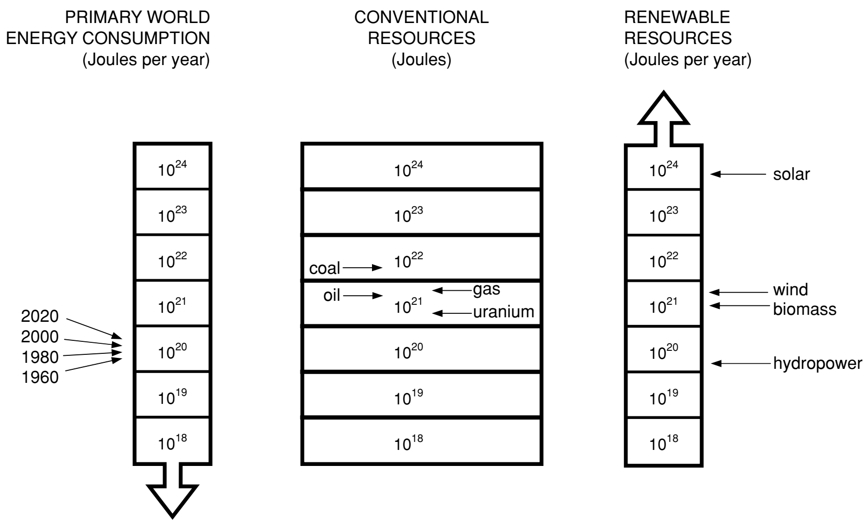

FIGURE 1.1 Global proven conventional resources of coal, oil, natural gas and uranium (used in non-breeder mode), as compared with world primary energy consumption, and the total energy per year available in the renewable resources of solar, wind, biomass and hydropower.

(that is, uranium used in thermal nuclear reactors, which unlike fast reactors do not 'breed' additional nuclear fuel). Also shown on the left are the world's primary energy consumption in 1960, 1980 and 2000, and predicted global consumption in 2020. It is clear that proven fossil fuel resources are within sight of being used up; at the current rate of usage, we have enough conventional oil and gas to last only a few more decades. More may well be discovered, and additional resources such as tar sands and methane hydrates may prove to be recoverable in an economically and environmentally acceptable way, but even then the hydrocarbon flame must go out within a few hundred years.

On the right of Figure 1.1 is the Earth's energy income from the renewables, that is, those energy sources that are powered by natural flows of energy from the sun and in the wind, waves and so on. At the top is the amount of solar energy absorbed by the Earth in one year, showing that the sun is by far our most abundant renewable energy resource. Every 44 minutes, sufficient energy from the sun strikes the Earth to provide the entire world's energy requirements for one year. The energy driving most of the other renewables, notably biomass, also derives partly or wholly from the sun.

Technical innovation in energy supply

In a globally warming world grown accustomed to cheap, subsidised fossil fuel power, incentives to encourage the use of renewable energy and more energy-efficient technology in a low-carbon economy are both necessary and justified. Internationally, the UK is signed up to the UN's Kyoto Protocol to curb the country's carbon dioxide emissions. Internally, the government has set the ambitious target of reducing national CO_2 emissions by 21.5 per cent by the year 2010 from the 1990 baseline. We have the (imperfect) beginnings of a carbon tax in the Climate Change Levy, and the new Renewable Energy Obligation will oblige electricity suppliers progressively to increase the proportion of their electricity sourced from renewables up to 10 per cent by 2010. Moving much beyond that figure would require our inflexible electrical transmission system to be reconfigured to accommodate fluctuating power inputs from renewables.

New methods of storing electricity would also be very helpful, and in this context the Cambridge region is host to a pioneering facility under construction at Little Barford, on the Cambridgeshire/Bedfordshire border. This is Regenesys, the world's largest secondary battery, with a charge/discharge cycle involving concentrated solutions of sodium polybromide/bromide and sodium sulphide/polysulphide, designed to store 120 MWh of electricity and discharge it at a nominal power rating of 15 MW.

On the horizon is the emergent hydrogen economy, brought closer by significant advances in the technology of PEMFCs (Proton Exchange Membrane Fuel Cells), likely to find their way into a new generation of electric cars over the next few years. Cambridge University itself will soon be entering the hydrogen era through its USHER project, in which photovoltaic modules placed on the roof of an architectural colonnade in the new West Cambridge campus will generate electrical power to electrolyse water and make hydrogen that will power buses to shuttle us to and from the new site.

Technical innovation in fossil fuel generation can also help to bring a lower-carbon energy economy closer. Thanks to continuing improvements in turbine materials and design, combined cycle gas power stations now generate electricity at nearly 60 per cent efficiency. Various 'clean coal' technologies are also under development. In one notable pilot scheme, coal in the North Dakota coalfields is gasified *in situ* by steam injection, and the resulting syngas ($CO + H_2$) is brought to the surface. The carbon monoxide (CO) in the syngas is further reacted with water to produce carbon dioxide (CO_2) and more hydrogen (H_2).

The hydrogen is separated and used as a fuel while the CO_2 is sent to the Weyburn oil field in Canada, where it is injected, at the same time enhancing oil recovery and sequestering the carbon.

Many commentators believe that the deep cuts in CO_2 emissions that may prove necessary in coming decades cannot be achieved without building new nuclear plant to replace the world's ageing stock of pressurised-water and gas-cooled reactors. A new generation of smaller, passively safe nuclear reactors such as the new CANDU reactor and the South African pebble-bed reactor are likely to be built and tested, and more radical innovations in nuclear power, such as moving from the uranium cycle to the thorium cycle, are possible. One day we may master fusion power, and experiments on plasma containment continue at JET, the Joint European Torus facility at Culham, and elsewhere.

The sun and thermal uses of solar energy

Meanwhile we already have a fully functional fusion reactor, our sun. In astronomical terms, the sun is no more than a middle-sized, middle-aged star, but to us it is overwhelmingly important. Like all main-sequence stars, the sun burns hydrogen to helium, destroying some mass in the process and creating energy in accordance with Einstein's seminal equation $E = mc^2$, where E is energy, m is mass and c is the speed of light. The sun is losing mass at the brisk rate of 4.5 billion kg per second and correspondingly beaming out about 10^{26} W of radiant power more or less uniformly into all directions in space. The Earth intercepts about one-billionth of this power, and it is this absorbed solar energy that keeps the Earth's surface at a habitable global mean temperature of 288 K instead of the 2.3 K characteristic of deep space and has enabled the creation and evolution of life on Earth.

Modern attempts to turn the sun's radiant energy into other energy forms date back to the nineteenth century. Several early collector designs, such as the Mouchot Sun Machine shown in Figure 1.2, were based on parabolic dishes aimed at the sun to concentrate its rays at a focal point, thereby reaching a temperature capable of driving an engine. In a modern solar power tower system, of which there are a few prototypes such as Eurelios, in Adrano, Sicily, and Solar Two in Barstow, California, a field of heliostats (mirrors) tracks the sun and reflects direct sunlight onto a receiver mounted on a central tower.

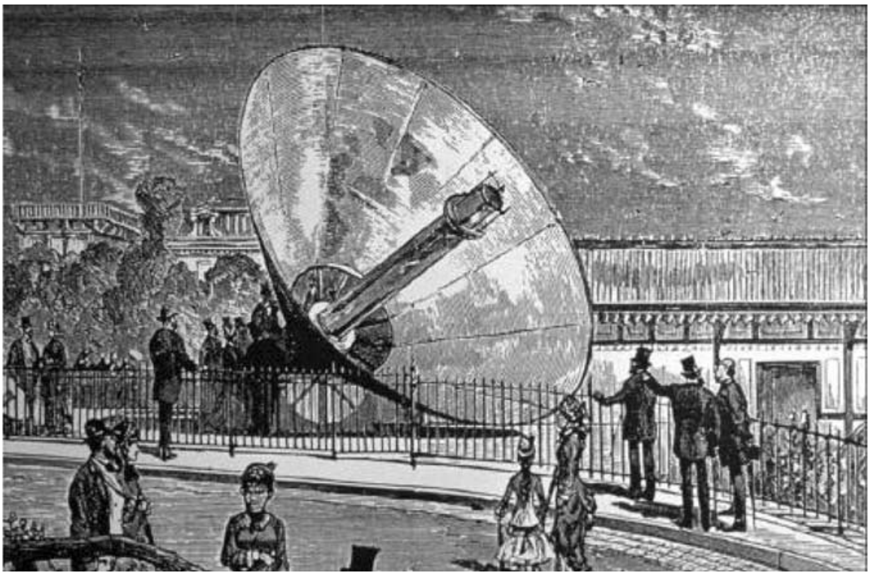

FIGURE 1.2 The Sun Machine invented by the French mathematician Augustin Mouchot, exhibited at the World Fair in Paris in 1878, could power a half-horsepower engine.

Power tower systems usually achieve solar concentration ratios of 300 to 1500, and operate at temperatures from 550 °C to 1500 °C, easily capable of driving a steam generator.

Focussing sunlight about one axis rather than two requires paraboloidal troughs rather than dishes. The Kramer Junction Company in the Mojave Desert in California is the world's largest solar thermal power station, turning out 354 MW electricity from east–west oriented troughs, along the focal line of which there runs a pipe containing a heat-transfer oil. This provides heat to a conventional steam generator, and back-up gas is used to provide constant output power on dull days.

Nearer home, a company in Foxton called HelioDynamics (www.hdsolar.com) is developing a range of hybrid solar thermal/electric converters, aiming for the commercial and industrial market in areas where stand-alone heat and power is needed because of poor security of electricity supply. The power comes from photovoltaic cells mounted at the focal spot of the solar concentrator, and the heat from cooling them.

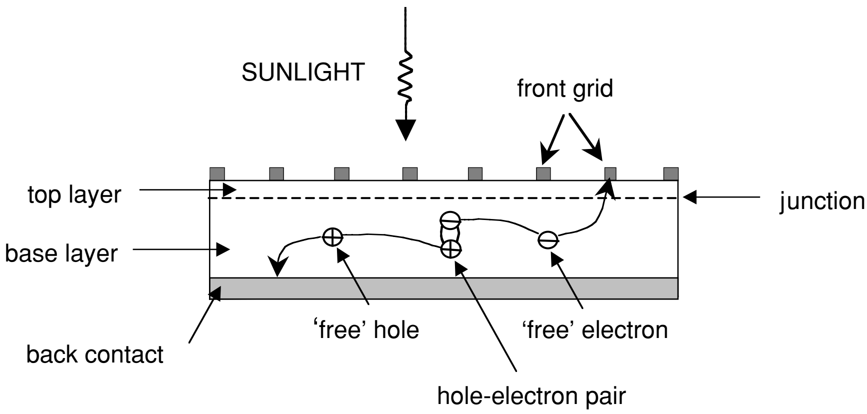

FIGURE 1.3 In a 'classical' solar cell, the junction between the electrically dissimilar top and base layers contains a built-in electric field that separates the hole–electron pairs generated by photon absorption.

Finally, as regards thermal applications of solar energy, flat-plate solar thermal collectors are widely used in sunny parts of the world to heat water for domestic and commercial use. In the UK, these are more cost-effective if self-built.

Direct conversion of solar energy: photovoltaic cells

Rather than using sunlight as a source of heat, one can use it as a stream of photons (quantised packets of radiant energy) in so-called direct conversion or photoconversion devices. These work not because they are heated by the sun, but because they separate hole–electron pairs generated by the absorption of solar photons, as shown schematically in Figure 1.3.

Photovoltaic cells, also known as solar cells, are by far the most successful man-made direct solar converters. These are flat, thin semiconductor devices, usually made of crystalline or amorphous silicon, that generate direct low-voltage electric power when illuminated. Hole–electron pair separation normally occurs at the junction between the top-layer and base-layer semiconductor, as shown in Figure 1.3. Photovoltaic power can be generated anywhere – in temperate or tropical locations, in urban or rural environments, in distributed or grid-feeding mode – and the modules are silent and non-polluting in operation. As a fuel-free distributed source of electricity, photovoltaic arrays