# 1 New electricity technologies for a sustainable future

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## 1.1 Introduction

One technological innovation more than any other accelerated the development of civilisation in the twentieth century – electricity. The first awakening of the electricity industry occurred in the latter half of the nineteenth century with the competing systems of George Westinghouse and Thomas Edison. Following the invention of the incandescent light bulb in 1879 electricity developed rapidly, until, by the end of the twentieth century, not only had power networks spanned most of the planet but also whole new industrial sectors in computing, communications and entertainment had emerged as a direct consequence of developments in electricity.

In these early years of the twenty-first century electricity is once again poised to permit fundamental shifts in the nature of our civilisation. We face a future in which concerns for our global environment, for social welfare and for stable market economics are all linked to the future development of electricity systems. Will electricity remain a reliable, large-scale centralised technology dominated by supply-side concerns? Or will it in future decentralise and move to a distributed model with far greater consideration given to end use? This book explores the potential for various electricity technologies to contribute to economic, social and environmental sustainability. As noted in Michael Grubb and Janus Bialek's foreword this book arises from a UK government initiative, and UK policy towards climate change forms the contextual background for the presentations in the book. In 2003 in the United Kingdom a government Energy White Paper produced by the Department of Trade and Industry (DTI, 2003) set out ambitious long-term aspirations for carbon reduction by 2050. This position and its consequences for the development of an electricity system in a country that has led the world in market-based electricity reforms is bound to be of interest both in the United Kingdom and internationally.

## 1.2 Electricity and carbon

With the significant exceptions of nuclear power and large-scale hydroelectricity the electricity system of the twentieth century relied upon the combustion of fossil fuels – initially coal and oil, and now increasingly natural gas. The Brundtland Commission's definition of sustainability requires that a sustainable electricity system must be able to meet current needs without compromising the ability of future generations to meet their own needs (World Commission on Environment and Development, 1987). As such, electricity systems based upon the depletion of finite fossil fuel reserves are fundamentally unsustainable. Sustainability is far more than an environmental concern, and in recent years attention has focused on three central pillars of social, environmental and economic sustainability – or, more colloquially, the three Ps of people, planet and profits.

The above formulation of sustainability allows for weaknesses in one of the three areas to be compensated for by measures elsewhere. For instance, environmental damage might be mitigated via active remediation funded from the profits of the activity. Much of the electricity industry has, however, relied upon the even weaker paradigm of 'deplete and innovate'. That is, a belief that natural resources should be depleted without any concern for future resource availability because, as primary fuels become scarce, technological innovation will be spurred, and via such technology-led innovations the necessary societal shifts will occur. The shift from whale and seal oil to mineral oil in the nineteenth century might be regarded as a good example of such thinking.

While the lack of sustainability arising from resource depletion, the operation of liberalised electricity markets ensuring socially sustainable electricity services and the safety of the industry are all important concerns, this book is dominated by one aspect of sustainability in particular: the stability of the global climate. The editors of this book are not climate scientists and it is not the purpose of this book to review the scientific literature concerning anthropogenic greenhouse gas emissions (GHGs) and their effects on global climate. Rather, we take on trust the advice of the majority of scientific opinion that such effects are occurring and that they are dangerous. These concerns more than any other shape the discussion of a sustainable future for electricity in the chapters that follow.

While some economies, such as that of the United Kingdom, have shown that economic growth can be achieved concomitant with decreased energy intensity, the global picture is far from encouraging. Across a swath of developed countries, economic growth and, in

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Table 1.1 *World total final consumption (Mtoe)*

| | 1971 | 2002 | 2010 | 2030 | 2002–2030[a] |
|---|---|---|---|---|---|
| Coal | 617 | 502 | 516 | 526 | 0.2 |
| Oil | 1,893 | 3,041 | 3,610 | 5,005 | 1.8 |
| Gas | 604 | 1,150 | 1,336 | 1,758 | 1.5 |
| Electricity | 377 | 1,139 | 1,436 | 2,263 | 2.5 |
| Heat | 68 | 237 | 254 | 294 | 0.8 |
| Biomass and Waste | 641 | 999 | 1,101 | 1,290 | 0.9 |
| Other Renewables | 0 | 8 | 13 | 41 | 6.2 |
| Total | 4,200 | 7,057 | 8,267 | 11,176 | 1.6 |

*Note:*
[a] Average annual percentage rate of growth.

*Source:* IEA (2004a, p. 68).

Table 1.2 *Share of electricity in energy demand by sector (%)*

| | OECD | | Transition economies | | Developing countries | |
|---|---|---|---|---|---|---|
| | 2002 | 2030 | 2002 | 2030 | 2002 | 2030 |
| Total final consumption | 20 | 22 | 13 | 15 | 12 | 20 |
| Industry | 25 | 27 | 18 | 22 | 17 | 25 |
| Residential | 32 | 38 | 11 | 14 | 8 | 20 |
| Services | 48 | 57 | 24 | 25 | 31 | 47 |

*Source:* IEA (2004a, p. 193).

particular, the growing share of the service sector and new applications have contributed to a growth in demand for electric energy. In developing countries, economic growth and population growth have combined with increased access to service – while an estimated 1.7 billion of their population are yet to be connected – to ensure a higher rate of increase in demand for electricity. Between 2002 and 2030 the worldwide final consumption of electricity is expected to grow at 2.5 per cent per annum (higher than other energy sources), while the relative share of electricity in total final energy consumption will increase from 16 to 20 per cent (see table 1.1). In the same period the share of electricity in total energy demand for major sectors of the economy in OECD, transition and developing countries is expected to increase (table 1.2).

Conventional technologies for the production, conversion and consumption of energy account for a significant share of the environmental

Table 1.3 *Energy-related $CO_2$ emissions (million tonnes)*

| | OECD | | Transition economics | | Developing countries | | World | |
|---|---|---|---|---|---|---|---|---|
| | 2002 | 2030 | 2002 | 2030 | 2002 | 2030 | 2002 | 2030 |
| Power Sector | 4,793 | 6,191 | 1,270 | 1,639 | 3,354 | 8,941 | 9,417 | 16,771 |
| Industry | 1,723 | 1,949 | 400 | 618 | 1,954 | 3,000 | 4,076 | 5,576 |
| Transport | 3,384 | 4,856 | 285 | 531 | 1,245 | 3,353 | 4,914 | 8,739 |
| Residential and Services | 1,801 | 1 950 | 378 | 538 | 1,068 | 1,930 | 3,248 | 4,417 |
| Other[a] | 745 | 888 | 111 | 176 | 605 | 1,142 | 1,924 | 2 720 |
| Total | 12,446 | 15,833 | 2,444 | 3,501 | 8,226 | 18,365 | 23,579 | 38,214 |

*Note:*
[a] Includes international marine bunkers (for world totals only) and other transformation and non-energy use.

impacts from pollutants and climate change. While electricity is essentially a clean energy source at consumption, a variety of environmental impacts are associated with its generation. ‘By 2030, the power sector could account for almost 45% of global energy-related $CO_2$ emissions. Carbon-dioxide emissions from power stations in developing countries will treble from 2002 to 2030. In 2030, coal plants in developing countries will produce more $CO_2$ than the entire power sector in the OECD in that year’ (IEA, 2004a). As table 1.3 shows, by 2030 global $CO_2$ emissions levels are forecast to increase to 38 billion tonnes – that is, a 62 per cent increase in relation to 2002. 50 per cent of this increase is expected to take place in the electricity sector.

Worldwide, investments in electricity between 2001 and 2030 have been projected at approximately $9,481 billion, a substantial amount by most measures (figure 1.1). However, this is still equivalent to only about 1 per cent of world GDP. Nearly one-half of these investments will be in generation facilities, and the other half in transmission and distribution networks. In addition to signifying future growth in demand for electricity, this represents significant capital and natural resource requirements, as well as environmental impacts if the current pattern of supply and demand persists. Research and development in new and emerging technologies can offer significant improvements in all the above areas, through technical progress and improved cost-effectiveness. However, despite their considerable potential for improvement, the current level of energy R&D

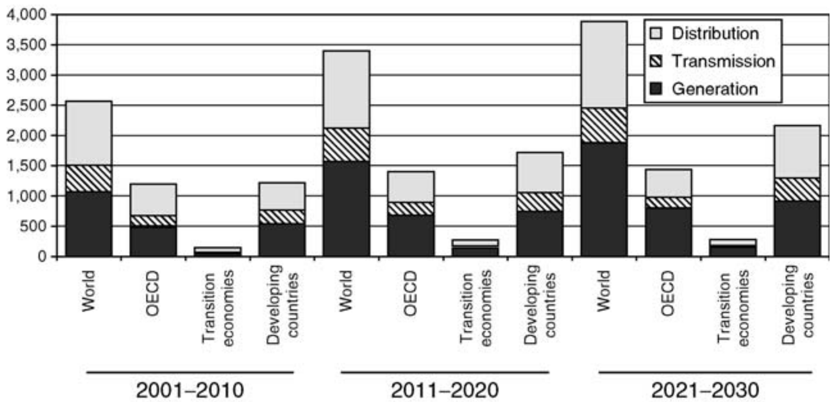


Figure 1.1. Worldwide investments in electricity, 2001–2030 ($ billion 2000).
Source: IEA (2003).

spending constitutes only a fraction of future capital needs. In other words, the potential economic, environmental and social returns from energy R&D investments are very substantial indeed.

## 1.3 Electricity and renewables

The above analysis of the significance of electricity suggests the importance of the introduction of renewable electricity generation if serious reductions in the total amount of $CO_2$ produced are going to be made. The potential for a large contribution is high, because the current contribution of renewables is modest and declining. The share of renewables in electricity generation fell from 24.1 per cent to 15.1 per cent between 1970 and 2001 in IEA countries (IEA, 2004b) This was primarily due to the dominance of hydro in total renewable generation (86% of all renewables) and the rapid growth of electricity demand since 1970.

With this in mind, the European Union has set a target of 21 per cent renewables by 2010, against 15.2 per cent in 2001, which comprises a range of varying national targets (see European Commission, 2004). There are a range of subsidy and support mechanisms for renewable energy sources in place in the Union, although these are not yet harmonised across member countries. However, it may be argued that, to the extent that conventional energy sources also receive subsidies and support, the effectiveness of subsidies and support mechanisms for renewable energy sources and their competitiveness may be reduced. In 2001 the total amount of energy subsidies in the EU-15 was estimated at about

€29 billion, of which about €5 billion were earmarked for renewable sources (EEA, 2004). This is while a significant amount of harmful environmental impact has been attributed to subsidies to conventional energy sources (OECD, 2003).

Among the most ambitious of these national targets is that of the United Kingdom, which has a target of 10 per cent by 2010, against 2.4 per cent in 2003. The EU targets are enshrined in the 2001 Directive (2001/77) on the Promotion of Electricity from Renewable Energy Sources (known as the 'RES-E' Directive). These targets for electricity from renewables are in the context of the European Union overall Kyoto commitment to an 8 per cent reduction in 1990 $CO_2$ emission levels by 2010.

In addition, the United Kingdom has an aspiration to a 20 per cent renewables contribution to electricity generation by 2020. It also has a national goal of a 60 per cent reduction in 1990 $CO_2$ emission levels by 2050. This 2050 target is not associated with electricity specifically but, given the fact that electricity is expected to make a disproportionately large contribution to cutting total $CO_2$ emission levels in both 2010 and 2020, it is safe to assume that the government's 2050 target implies at least a 60 per cent renewables contribution to electricity generation by that date.

The United Kingdom's National Audit Office (2005) recently reviewed the government's expenditure in supporting renewable electricity generation and the likelihood of it meeting its targets. The 2010 target is assessed as challenging, with a strong possibility that the government will only reach a 7.5 per cent renewables level by then. This is in spite of the current policy of requiring suppliers to purchase increasing amounts of green certificates up to the amount of the target of 10 per cent by 2010. In 2003–4 renewables accounted for 2.4 per cent of electricity generation, significantly lower than the obligation level of 4.3 per cent. The policy comes at a price, with the expected total cost of renewables support being £700 million per annum between 2003 and 2006, of which two-thirds is paid by consumers through the renewables obligation. The cost to consumers is expected to be equivalent to a 5.7 per cent increase in the price of electricity by 2010.

The National Audit Office (2005) concluded that the roll-out of renewables faced several major difficulties. These were difficulties in gaining planning permission for new generation sites, timely grid reinforcement, low market electricity prices, uncertainty that the renewables obligation scheme will continue into the longer term and the need for additional funding for new technologies.

In 2003 38 per cent of the United Kingdom's carbon dioxide emissions were from energy industries, 21 per cent from road transport,

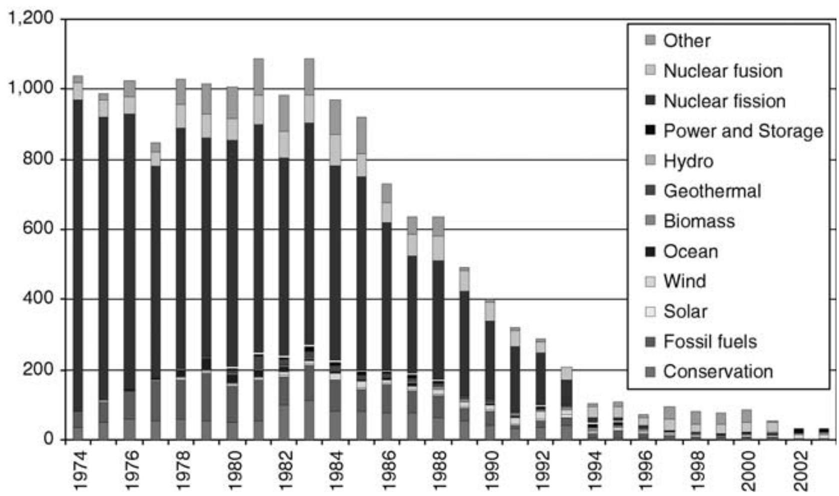


Figure 1.2. UK government energy R&D expenditure ($ million 2003 prices and exchange rates).
Source: IEA, Energy R&D Database.

18 per cent from other industries and 15 per cent from residential fossil fuel use (DEFRA, 2005). Since 1990 energy industry emissions have reduced by 10 per cent and other industrial emissions by 11 per cent, while residential emissions have increased by 11 per cent and road transport emissions by 8 per cent.

Although UK government targets for renewables generation sources are challenging, the government's support for renewables R&D is modest at present. UK government R&D is shown in figure 1.2. Liberalisation in the early 1990s was accompanied by a precipitate decline in total R&D expenditure. R&D expenditure on renewables has always been relatively small, and although it has picked up recently it remains below the levels of the 1970s. It remains to be seen whether market support mechanisms can deliver the innovation and the penetration of new technologies that the government might like.

## 1.4 Purpose and structure of the book

The electricity supply system has a pivotal role to play in ensuring the environmental and social sustainability of future economic and energy systems due to the size of its current contribution to emissions of greenhouse gases. A key factor in achieving a sustainable electricity system is technological progress at all levels, from generation through to end use. The promise of technological progress allows us to envisage electricity systems for the future that are radically different from today's conventional systems. The systems' main characteristics have, since the inception of the industry, and the triumph of George Westinghouse's alternating current approach, remained largely unchanged. At the same time, in no other sector has there been such a wide range of emerging and prospective technologies promising to transform nearly every aspect of the organisation and operation of industry and commerce. As a result, it is important to survey the new electricity technologies and to assess how these may shape the future of our electricity system.

This book is intended as a broad overview of the issues and progress path of new electricity technologies, and as an accessible resource to academics, decision-makers and others with an interest in the future of electricity systems. It allows all the authors to make their own claims for the technologies they discuss. As editors we do not offer an economic assessment of these claims, nor have we sought to limit their enthusiasms, as this would be inappropriate for a book with a primary focus that is technological and visionary. Some implicit costs are contained in the analysis of chapter 2, but the purpose of this chapter is similarly visionary, aiming to provide a set of plausible futures in order to stimulate discussion rather than supply a costed statement of likely futures.

Collectively, the chapters in this book present a holistic vision of the future. Written by leading experts in their respective technology areas, they review the state of the art of these key areas in an accessible manner and offer insights as to how these may evolve to shape the future of the industry. New technologies are expected to transform nearly all aspects and stages of the electricity system, from how electricity is generated, transported through networks, stored for later use and, finally, consumed. The organisation of the book broadly follows the structure and hierarchy of activities in the electricity system.

As part of the book we have included an opening chapter (chapter 2) outlining some scenarios for the future development of the electricity system in the United Kingdom that illustrate the place of each of the technologies we discuss in the book.

Chapter 2 is important in postulating the role and significance of the particular technologies that we examine. It is also significant in outlining different possible futures for the UK electricity sector and indicating something of the range of possibilities that exist. In line with the long-term objectives of the UK government to reduce carbon emissions by 60 per cent by 2050, the electricity sector is examined at that date. Six scenarios are outlined. To contrast two of the results we examine the *Business as Usual* scenario and the *Green Plus* scenario.

Under *Business as Usual*, economic growth is the same as recently, technological change is evolutionary, environmental attitudes are similar to now and the market remains liberalised. The result is that, in 2050, of total capacity 30 per cent is renewables and 50 per cent is conventional large plant generation. There is significant use of advanced control of the grid, strategic energy storage and asset management. Under *Green Plus* the market remains liberalised and economic growth remains similar, but technological change is revolutionary (more rapid) and attitudes to protecting the environment from GHGs become much more strongly positive. The result is that 80 per cent of electricity is generated from renewables and zero in large conventional power stations. Interconnectors and offshore transmission are very important, sophisticated network control is utilised and there is significant use of storage, micro-grids and demand-side management. Other scenarios lie between these extremes. Under the *Green Plus* scenario wind provides 40 –45 per cent of total energy, photovoltaic generation 3–5 per cent, biomass 25 per cent, wave 5–10 per cent. Micro-renewables account for 20 per cent of electricity production. There is no role for nuclear or carbon capture. However, significant use is made of superconductivity in high-voltage transmission links, advanced power electronics, energy storage, efficient end-use technologies and electric transport. Hydrogen is used in transport, but is produced from conventional sources.

The subsequent chapters on electricity technologies cover electricity production from a number of new technologies and improved conventional sources. Here, technical progress has been made on a number of fronts. Although the exact role of individual technologies is unclear, it is plausible to assume that renewable and other sustainable options will be available and these will account for a larger share of electricity generation. Many of these are likely to be smaller in scale than current conventional technologies. Furthermore, the intermittent nature of their production patterns will pose challenges for the electricity system and for end users. The intermittency of some generation technologies will not necessarily lead to poor reliability for consumers. Rather, a coevolution of patterns in generation, transmission, distribution and end use is expected, so that all consumers will receive the electricity-based services they require at the times of their choosing and at affordable prices.

The technologies are presented in four parts.

Part I examines the most promising new renewable technologies. We include wind (chapter 3) in this as being new and exclude hydro as being old and limited in its future scope. We also review the prospects for solar energy (chapter 4), biomass (chapter 5) and wave energy (chapter 6).

All four of these technologies feature prominently in the *Green Plus* scenario noted above.

Part II reviews the key technologies that could serve to deliver carbon benefits from existing thermal technologies. We begin by looking at how conventional fossil fuel technologies might reduce their carbon emissions by employing carbon capture (chapter 7). We go on to examine how the future of nuclear power might develop (chapter 8) and how a trend towards miniaturisation might facilitate the use of efficient embedded generation technologies at the household level (chapter 9).

Part III looks at technologies that support the wider use of renewable energy by facilitating its conversion to more usable forms or by improving the reliability and accessibility of remotely produced renewable energy. Thus we examine the use of superconductors to facilitate electrical loss reduction in transmission systems (chapter 10) and advances in power electronics to accommodate frequency and voltage disturbances created by renewables (chapter 11). We also look at the prospects for the use of hydrogen energy as a carrier for renewable electrical energy for use throughout the day and in transport (chapter 12). We conclude by looking at how new storage technologies, such as using compressed air, can facilitate the connection of intermittent renewables (chapter 13).

Part IV examines the role of technology in reducing the demand for energy by using electrical energy more efficiently. In this part we survey possible technological advances in buildings (chapter 14) and industry (chapter 15) that would reduce demand, and the use of electrical transportation to facilitate the use of clean electricity and reduce overall GHG production (chapter 16). We also review the scope for the use of smart meters that facilitate greater efficiency in the domestic demand for electricity (chapter 17).

The electricity system of the future is likely to be more flexible and responsive than that in operation today. One has only to look at the evolution of telephony in the last thirty years, from a situation of expensive, centralised monopoly providers using fixed infrastructures to the world of today, with diversity of quality, far wider flexibility of use, far greater availability of services and a real move to competitive markets. We appear to be in the early stages of a similar revolution in the electricity system.

## 1.5 Technology chapter summaries

The different chapters in this book review the state of the art and the potential impact of a range of new electricity technologies. The chapters cover various generation and end-use technologies, as well as storage