# New Electricity Technologies for a Sustainable Future

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February 2006

CWPE 0608 *and* EPRG 0512

# NEW ELECTRICITY TECHNOLOGIES FOR A SUSTAINABLE FUTURE

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## Abstract

There is a growing concern over continuous reliance of our economic and energy systems on conventional electricity sources and their long-term environmental, climate change, and security of supply implications. At the same time, much hope and belief is vested in the ability of future technological progress to tackles these issues. However, informed academic analysis and policy debates on the future of the electricity systems will need to be with reference to the current state and prospects of the technological options. This paper constitutes the introduction chapter in the forthcoming book "***Future Electricity Technologies and Systems***".[†] The book comprises contributions from leading experts in their respective technology areas. The chapters present the state of the art and the likely progress paths of conventional and new electricity generation, networks, storage, and end-use technologies. In this paper we review the growth trend in electricity demand and carbon emissions. We then present a concise overview of the chapters. Finally, we discuss the main contextual factors that influence long-term technological progress.

***November 2005***

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[†] ***Future Electricity Technologies and Systems***
**Editors: Tooraj Jamasb, William J. Nuttall, Michael G. Pollitt (University of Cambridge)**
**Series: Department of Applied Economics Occasional Papers (No. 67)**
**Cambridge University Press – May 2006**
**ISBN-10: 0521860490 | ISBN-13: 9780521860499**

## 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 discovery 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's preface, 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 UK a government Energy White Paper (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 that has led the world in market based electricity reforms is bound to be of interest both in the UK and internationally.

## 2. Electricity and carbon

With the significant exceptions of nuclear power and large-scale hydro electricity 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 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 particular the growing share of the service sector and new applications has contributed to a growth in demand for electric energy. In developing countries, economic and population growth has combined with increased access to service - while an estimated 1.7 billion of their population are yet to be connected. This will ensure a higher rate of increase in demand for electricity in these countries. Between 2002 and 2030, the world-wide final consumption of electricity is expected to grow at 2.5 percent per annum (higher than other energy sources) while the relative share of electricity as total final energy consumption will increase from 16 to 20 percent (Table 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 2).

**Table 1: World Total Final Energy Consumption (Mtoe)**

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

| | 1971 | 2002 | 2010 | 2030 | 2002-2030* |
|---|---|---|---|---|---|
| **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% |

* Average annual rate of growth.

**Table 2: Share of Electricity in Energy Demand by Sector (%)**

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

| | 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 |

Conventional technologies for production, conversion, and consumption of energy account for a significant share of environmental impacts from pollutants and climate change. While electricity is essentially a clean energy source at consumption, a variety of environmental impacts are associated with generation of electricity. “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, 2004). As Table 3 shows, by 2030, Global $CO_2$ emissions levels will increase to 38 billion Tonnes that is a 62 percent increase in relation to 2002. 50 percent of this increase is expected to take place in electricity sector.

**Table 3: Energy-Related $CO_2$ Emissions (million tonnes)**

**Source: IEA (2004a, p.75)**

| | 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*** | 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 |

* Includes international marine bunkers (for world totals only), other transformation and non-energy use.

The world-wide investments in electricity between 2001 and 2030 have been estimated at approximately $US bill. 9,481, a substantial amount by most measures (Figure 1). However this is still only about 1% of world GDP. Nearly, one-half of these investments will be in generation facilities and the other half in transmission and distribution networks.

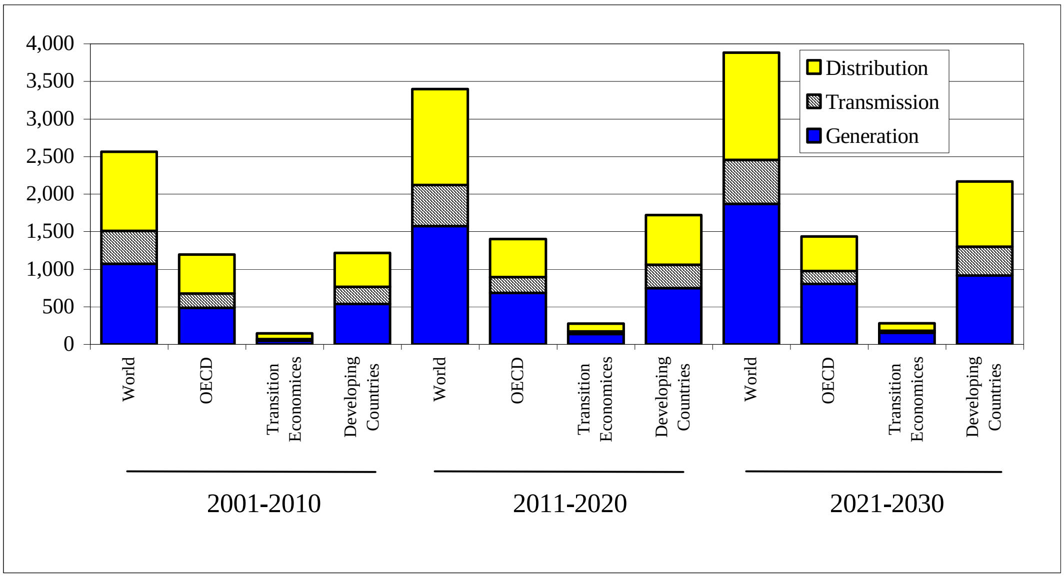


**Figure 1: World-Wide Investments in Electricity 2001-2030 ($US bill. 2000)**

**Source: IEA (2003)**

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 (R&D) in new and emerging technologies can offer significant improvements in all the above areas through technical progress and improved cost effectiveness. However, despite the considerable potential for improvement, the current level of energy R&D 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 indeed very substantial.

## 3. Electricity and renewables

The above analysis of the significance of electricity suggest 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% to 15.1% 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 EU has set a target of 21% by 2010 against 15.2% in 2001 which comprises a range of varying national targets (see European Commission, 2004). There is a range of subsidy and support mechanisms for renewable energy sources in place in the EU, although these are not yet harmonised across member countries. However, it may be argued that, to the extent 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 EU-15 have been estimated at about 29 billion euros of which about 5 billion euros 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 the EU national policies for renewables is the UK which has a target of 10% by 2010 against its current 2.4% in 2003. The EU targets are enshrined in the 2001 Directive (2001/77) on 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 EU’s overall Kyoto commitment to an 8% reduction in 1990 $CO_2$ emission levels by 2010.

In addition the UK has an aspiration to a 20% renewables contribution to electricity generation by 2020. It also has a national goal of a 60% 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% renewables contribution to electricity generation by that date.

The UK'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 7.5% renewables 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% by 2010. In 2003-04 renewables were 2.4% of electricity generation, significantly lower than the obligation level of 4.3%. The policy is expensive with the total cost of renewables support being £700m p.a. 2003-2006, of which 2/3 is paid by consumers through the renewables obligation. The cost to consumers is expected to be equivalent to a 5.7% increase in the electricity price 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 UK's carbon dioxide emissions were from energy industries, 21 per cent from road transport, 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 UK government's support for renewables R&D is currently modest. UK government R&D is shown in Figure 1. 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 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.

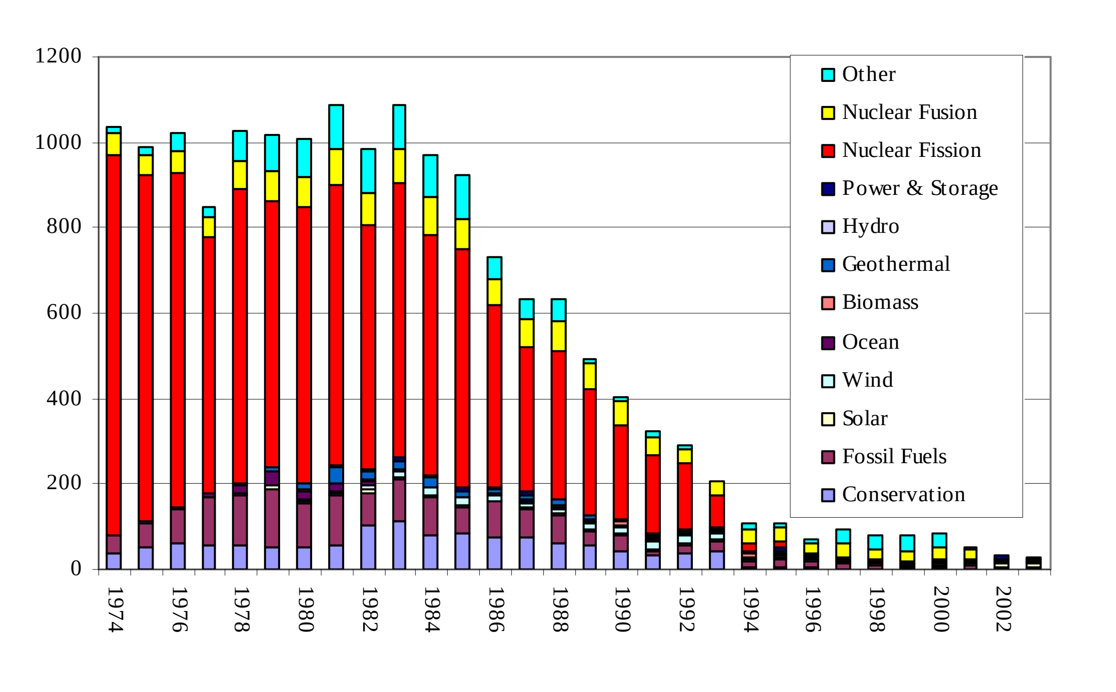


**Figure 2: UK Government Energy R&D Expenditure**
**(Million US$ (2003 prices and exchange rates)**
**Source: International Energy Agency (IEA), Energy R&D Database**

## 4. Purpose and structure of the book

The electricity supply system has a pivotal role to play in ensuring environmental and social sustainability of future economic and energy systems due to the size 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 the 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. It is therefore 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. The book allows each of the authors make their own claims for the technologies they discuss. As editors we do not offer an economic assessment of these claims as this would be inappropriate for a book whose primary focus 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 to stimulate discussion rather than a costed statement of likely futures.

Collectively, the chapters in this book present a holistic vision of the future. The chapters in this book are written by leading experts in respective technology areas. They review the state of the art of key technology 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 UK which 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 six 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% 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% is renewables and 50% 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, however technological change is revolutionary (more rapid) and attitudes to protecting the environment from GHGs become much more strongly positive. The result is that 80% of electricity is generated from renewables and zero in large conventional power stations. Interconnectors and offshore transmission is very important, sophisticated network control is utilised and there is significant use of storage, microgrids and demand side management. Other scenarios lie between these extremes. Under the Green Plus Scenario wind provides 40-45% of total energy, photovoltaic generation is 3-5%, biomass 25%, wave 5-10%. Micro-renewables are 20% of electricity production. There is no role for nuclear or carbon capture. However significant use is made of super-conductivity 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. Intermittency of some generation technologies will not necessarily lead to poor reliability for consumers. Rather a co-evolution of patterns in generation, transmission, distribution and end use is expected so that all consumers will receive the electricity based services they require at times of their choosing and at affordable prices.

The technologies are presented in four parts.

Part One 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 Two reviews the key technologies which 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 miniturisation might facilitate the use of efficient embedded generation technologies at the household level (Chapter 9).

Part Three looks at technologies which support the wider use of renewable energy by facilitating its conversion to more useable forms or 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 across the day and in transport (Chapter 12). We conclude by looking at how new storage technologies such as by using compressed air can facilitate the connection of intermittent renewables (Chapter 13).

Part Four examines the role of technology in reducing the demand for energy by using electrical energy more efficiently. In this section we survey possible technological advances in buildings (Chapter 14) and industry (Chapter 15) which would reduce demand and the use of electrical transportation which would facilitate use of clean electricity to reduce overall GHG production (Chapter 16). We also review the scope for the use of smart meters which 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 only has 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 variable 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.

## 5. Technology chapter summaries

The different chapters in this book review the state of the art and potential impact of a range of new electricity technologies. The chapters cover various generation and end-use technologies as well as storage and power technologies that will enable more active transport networks and will allow the supply and demand sides to interact in new and innovative ways.

***Part One: Renewable Generation Technologies***

*3. Wind Power*

As the current renewable generation technology of choice wind is a good place to start this section of the book. In this chapter Morthorst reports on the very rapid growth of wind power in recent years. The economics of the technology are dominated by capital costs and this implies a significant sensitivity to discount rates adopted. A detailed breakdown of the cost structure of a 1MW wind turbine is presented. The recent trend in the sector is reported to be a move towards larger turbines with improved cost effectiveness over previous plans. The role of wind speed and wind resource intermittency is discussed in the context of wind power technologies and the economics of this form of electricity generation. The paper stresses the recent emphasis on offshore wind farms with anticipated power costs for a 3MW offshore turbine predicted to be 4.2 c€/kWh. This will be somewhat higher than the equivalent cost for onshore wind power production of 2.4 –3.0 c€/kWh. In such circumstances it is argued that onshore wind power will certainly be economically competitive with natural gas fuelled electricity and that offshore wind power systems will be not too far behind.

*4. Solar Energy: Photovoltaic Electricity Generation*

Mumtaz and Amaratunga open their chapter with a history of solar electricity and semiconductor photovoltaic technology. A text box describes the scientific fundamentals of photovoltaic technology and describes the voltage/current trade-offs to be made in deploying such technologies. The chapter discusses the main ways of fabricating photovoltaic cells and points to recent attempts to reduce the relatively high costs of production. One technology: amorphous silicon based photovoltaic, has the great benefit of being available in physically flexible (bendable) sheets. A key drawback of the technology, however, is its lower operating lifetime. The chapter emphasises both off-grid and on-grid applications of solar power. The former market is well developed, and while the back-up batteries associated with off-grid applications are expensive, an off-grid set-up is frequently significantly less expensive than the costly alternative of providing access to national grid infrastructures. For remote, unmanned, off-grid applications it is important to remember the costs of regular maintenance and cleaning for the efficient operation of these systems. On-grid applications, however, face a tougher economic climate. Despite this, costs have fallen substantially and are now far lower than generally perceived. Key to the economics of on-grid solar power are capital costs, maintenance, reliability and system lifetimes. Solar panels are however, unique among major electricity generation technologies, as they can be genuinely distributed close to the points of electricity use. They are particularly well matched to urban installation. In that context, the chapter discusses the relationship between solar panels and prestige architectural materials. Once the full costs of building construction, office use and energy demands are factored together solar power can appear very attractive. The chapter concludes with some forward-looking comments regarding possible technology innovations for both solar panel design and their end use.

*5. Biomass*

Bridgwater reviews bioenergy technologies. Bioenergy is a renewable source utilising wood, crops, and agricultural and forestry woods. In addition to being a source of electricity generation, biomass is the only renewable source that produces solid, gaseous, and liquid fuels for transport and other uses. The technology has the potential to be a part of sustainable future energy systems and comprises a range of approaches. These can broadly be grouped into biological conversion, physical conversion, and thermal conversion. This chapter focuses on thermal conversion processes. The main thermal processes reviewed in the chapter are combustion, gasification, and pyrolysis. Gasification offers the highest efficiencies among these technologies.

The overall power efficiencies of combustion technologies are between 15 and 35 percent. There are already examples of commercially successful operation of the technology. Emissions and ash handling remain technical issues in need of further progress. For gasification technologies, the power efficiencies are between 35 and 50 percent. Some of the gasification technologies exhibit both technological strength and market attractiveness. There is, however, limited operating experience with these technologies. Moreover, the technology faces high costs and non-technical barriers and requires integration in a biomass energy system. Pyrolysis technology is based on thermal decomposition in the absence of oxygen and much research is focused on fast pyrolysis for liquids production. Also here there are cost and non-technical barriers to overcome. Thermal bioenergy sources are likely to mostly come from small-scale plants and will thus need to compete with other sources at smaller scales. A combination of high value chemicals and low value fuels can improve the economics of bioenergy technologies.

*6. Wave energy*

In their chapter, Thorpe and Wallace discuss the considerable potential for the generation of electricity from wave energy in certain coastal and off shore locations. A particularly favourable location is off the northern coast of Scotland. The maximum exploitable resource is estimated at around 31 TWh in the UK (or around 7% of present demand). There currently exist working prototypes for the exploitation of on-shore wave using oscillating water column (OWC) technology. A variety of off-shore technologies are being explored. These offer the prospect of bigger and less unsightly facilities but have proved more technically challenging. Some of both types have performed successfully for a number of years at a single site. However they remain vulnerable to catastrophic damage during storms and currently suffer from very high capital costs relative to their energy capture. Interest in the technology is increasing, especially in the UK, where government funding is currently among the most generous. The chapter highlights three constraints to further development in the UK. The legacy of the failure of an earlier government supported push in the 1970s, the cost of connection to the electricity grid (which can be up to 50% of the capital cost of new projects) and the difficulty of getting planning permission.

***Part Two: Generation Technologies***

*7. Carbon capture*

Moving to the section addressing existing thermal technologies, Røkke examines the prospects for carbon capture. Some of the options to reduce the amount of man-made $CO_2$ emissions are the more efficient use of energy, and the use of low-carbon fuels. Many of the necessary improvements will be made possible via technological innovation. However, to the extent that fossil fuel-based generation technologies will continue to be used, carbon sequestration technologies can play a significant part in reduction or even utilisation of $CO_2$ emissions from electricity generation. The range of technological options for carbon sequestration includes pre-combustion, post-combustion, and oxy-fuel technologies. The $CO_2$ will then be transported and deposited in reservoirs or alternatively injected in oil reservoirs in enhanced oil recovery operations. The carbon capture is at a stage where further technical progress and cost reduction is needed through R&D and demonstration efforts.

*8. Nuclear energy*

Grimiston begins this chapter with an exploration of the barriers to a re-growth of nuclear power in western countries. He highlights four difficulties to be overcome: a low level of research and development, a shortage of skilled workers, poor public perceptions, and difficulties surrounding the management of radioactive wastes. The chapter provides a description of the fundamentals of nuclear fission and of nuclear power production. The problems of nuclear power are particularly associated with worsening economics of nuclear projects in the years after the Three Mile Island accident in the United States in 1979 and the Chernobyl disaster in the Ukraine in 1986. Nuclear power is characterised as a power technology with high capital costs and strong incentives towards economies of scale. Grimston counters the views of many commentators when he points out that nuclear power is not one technology, but many. As such it is unhelpful to talk about nuclear power as being ‘mature’ given that many potential nuclear power technologies are presently under-developed. He describes successive generations of nuclear power generation and discusses in some detail future Generation IV technologies and the technologies favoured by the US led Generation IV International Forum.

*9. Microgeneration*

For most of the post-Second World War period there was a tendency to increasing scale in power generation. In this chapter Biermann points out how this tendency was reversed in the 1990s with the emergence of combined cycle gas turbine technology that could be operated at much smaller scale than pre-existing coal fired plants. Now much smaller scales are being commercialised which are capable of being installed at the point of electricity consumption, all the way down to the household. This chapter discusses the emerging technologies: micro CHP plants down to 1 KW and renewable micro-generators such as the photovoltaic solar cell (solar PV). Many of these technologies are being developed privately, with the exception of solar PV and fuel cells, and offer considerable market potential. For example the market for household micro-CHP for instance is the market for boilers. These are replaced at 5-6% per annum in the UK. A 1.2 KW Stirling Micro-CHP unit can produce heat and an average of around 2400 kWh of electricity, mostly at periods of peak system consumption. Currently the purchasing cost (before installation) of these units is about twice as expensive as a conventional boiler and this is the major barrier to their adoption. However if these units were used to replace 30% of conventional boilers they could produce a quarter of domestic electricity demand and significantly reduce distribution and transmission system losses. The significance of this is that responsibility for generation dispatch will shift significantly from large scale power plants to small scale units, fundamentally changing how the system will need to be operated. In particular network investment will be required to install much more flexible switchgear and transformers at the local distribution level.

***Part Three: Electricity Conversion and Storage***

*10. Superconductors in the electrical power industry*

Moving on to supporting conversion and transmission technologies, Campbell starts his chapter with a history of the discovery and development of superconductivity. Recent decades have seen a move towards Type II alloy materials in the 1960s, the discovery of High $T_C$ superconductivity in 1987 and most recently the promise of magnesium diboride conductors. The main applications of superconductors to a sustainable energy future are listed as being in: motors and generators, energy storage, fault current limiters, power cables, and levitated trains. In many cases the main challenges are two fold – better materials and more efficient cooling. Superconductors are reported to be a low hazard technology and an environmentally benign contributor to improvements in electricity transmission, distribution and end use. It seems likely that applications of these relatively high cost and sophisticated technologies will be specific and selective rather than ubiquitous and pervasive in the electricity sector as a whole. The main barrier to wider deployment is argued to be the economic disadvantage of these efficient technologies in an artificially inexpensive fossil fuel based electricity system.

*11. Power electronics*

For Green and Aramburo the main promises of power electronics technologies are better flexibility and controllability of power systems. While power electronics technology is a mature technology that has proven useful in other areas from mobile phones to rail transport, its potential benefits for power systems are under-utilised.

The technological basis of power electronics is semiconductor devices able to switch large currents and voltages. Potential benefits of power electronics are in low and high power ratings in generation, supply side, demand side, and network control. Power electronics can facilitate use of new forms of generation sources and provide network reinforcement measures features not offered by traditional technologies. More specifically, important application areas for power electronics technologies are: (i) frequency and voltage transformation for connecting renewable sources to networks, (ii) reduction of voltage disturbance caused by generators in local distribution networks, (iii) improvement in stability and voltage tolerance from new power sources, and (iv) limiting negative impacts of intermittent sources on quality of supply.

The main challenges facing power electronics are high costs, high energy losses, and increase in system complexity resulting from extensive integration of such devices. Moreover, realisation of some of the potential benefits of power electronics is contingent upon changes in the design and practice aspects of power systems need to be altered.

*12. Sustainable Hydrogen Energy*

As Edwards and his co-authors point out in this chapter, the vision of a hydrogen-powered economy is one that many, including the European Commission, continue to take seriously. The value of hydrogen is that it can store and transport energy produced from intermittent sources (such as wind). Thus it could be used to provide electricity for use at different times and it can be used to power vehicles, thus facilitating the use of renewable electricity in road transport. The barriers to the widespread use of hydrogen are significant. In vehicles hydrogen is 2.5 times heavier than petrol per unit of energy and it also takes up 4-9 times more volume. It is also expensive and difficult to store safely. Another significant issue is the distribution of hydrogen. Petrol has an established distribution system. Investing in the hydrogen distribution pipe network would be very expensive, while the extra bulk of hydrogen makes tanker distribution significantly more expensive than petrol distribution.

However the potential of hydrogen remains high with an estimated global demand for fuel cell products (in portable, stationary and transportation power applications) to reach $46 billion by 2011. The authors conclude by suggesting that the viability of the hydrogen economy depends on political will to make hydrogen competitive in the near term and then to support a prolonged period of co-existence with fossil fuels until these run out.

*13. Electrical energy storage*

Ruddell reviews electrical energy storage technologies. A fundamental problem with electrical energy is that it is very expensive to store once it has been produced. Large scale pumped storage hydro is the only widely used way of converting and storing electricity and the expansion possibilities for this are limited. Electrical energy storage is an issue because of the uneven pattern of demand which means that the electricity system costs can be reduced if electricity can be produced at periods of low demand and stored electrical energy released at periods of high demand. Renewable electricity sources tend to be intermittent and difficult to synchronise with the demand imposing additional system costs in the absence of storage. This chapter investigates the state of storage technologies that could facilitate the increased use of renewables. It examines electrochemical storage (batteries and flow cells), electromechanical storage (pumped hydro, compressed air and flywheels) and electrical storage (superconducting magnetic energy storage and supercapacitors). All these technologies are challenging to make cost effective and some, such as battery technologies, have additional negative environmental impacts. Several have technical problems associated with the limited number of cycles of charging and discharging that they can be subjected to before failing. The most promising new technology is compressed air storage which can store electricity for up to 2 hours and offer power capacities of up to 3 GW but requires suitable underground sites (such as redundant mines) for the storage of the compressed air.

***Part Four: End-use Technologies and Patterns of Future Demand***

*14. Buildings*

Turning to demand reduction technologies, Eichhammer assesses the prospects for more energy efficient buildings. In the buildings sector, two long-term visions outline prospects of radical changes not only in the way buildings consume electricity but also interact with the supply side of the system. In the *integrated-world*, buildings are integrated into active networks that connect and co-ordinate a variety of new and conventional generation sources to buildings that also function as distributed supply sources. Advancements in a variety of components and networking technologies will be needed for realising these networks. Moreover, new technologies can help in managing supplies from intermittent renewable sources and reduce the transaction costs of integrating small-scale units in electricity systems. In the *component world* vision, the energy efficiency potential of buildings will reduce demand for energy to levels where interconnection to wider electricity systems will become uneconomic. In this world, technical progress in the components and materials used in appliances and in building shells can yield considerable energy savings and transform the conventional mode of supplying energy to buildings from centralised systems to self-sufficient and decentralised systems. Even further into the future, new technologies may transform building and vehicles into a major source of energy supplies to electricity systems.

*15. Industrial end-use technologies*

Price, Galitsky, and Worrell present the main aspects of industrial end-use of electricity. Industry accounts for about 40 percent of global commercial energy demand through a variety of applications. As the authors describe, an array of new technologies are on the horizon with the promise of improved efficiency in electricity end-use. Technological progress is expected at the level of small, medium, and large generation units for different industrial applications and scales. The paper focuses on three main categories of electricity-efficient technologies: efficiency improving technologies, efficient fuel switching to electricity, and industrial cogeneration of heat and power. Motor systems account for over half of industrial consumption of electricity. Here new types of motors, system design that match generation and end-use, and controls can contribute to more efficient use of electricity. New membrane technologies for use in a variety of separation processes will facilitate efficient fuel switching to electricity in different industries. Industrial self-generation based on new gassification or advanced cogeneration technologies can reduce the demand for electricity. Other new technologies such as fuel cells are also likely to become commercially available and widen the range of technological options for industrial applications.

*16. Transport*

Belmans and Vermeyen point out that the transport sector is the most rapidly growing source of GHG emissions. However electrically supplied transport modes may facilitate the substitution of cleanly produced electricity for fossil fuels. This chapter discusses the prospects for electric vehicles – both road and rail - in Europe. Electric vehicles require sophisticated frequency control to allow them to use power from the grid, while regenerative breaking allows them to substantially improve their energy efficiency by supplying power while moving downhill or breaking. Electric passenger trains using magnetic levitation technology can travel at up to 500 Km/h while offering reasonable energy efficiency due to the reduced friction. There exists greater potential for the use of inter-modal transport using electric freight trains to carry conventional fossil-fuel trucks. The chapter also looks at battery powered, hybrid powered and fuel cell electric road vehicles. In the near term the hybrid vehicle (where the combustion engine drives the generator which powers the vehicle) offers substantial energy efficiency advantages without requiring any external infrastructure investment. The authors conclude with a review of an IEA study that suggests that $CO_2$ emissions in 2020 from road and rail transport in western Europe could be reduced substantially by measures (such as fiscal incentives and better labelling) to encourage the deployment of electric vehicles. The impact on system electricity demand of such policies would be positive but negligible.

*17. Smart metering*

Devine-Wright and Devine-Wright discuss the prospects for electricity demand reduction by use of 'smart' meters. Traditional household electricity meters are only capable of recording the cumulative amount of electricity consumed by a household and have to be manually read in situ. 'Smart' meters are capable of two-way electronic information flow between the supplier and the household. This information flow can be frequent, multi-format, accurate, real-time and high quality. These meters offer the prospect of allowing the price and quantity of electricity consumed to be varied remotely in real time subject to the terms of a contract which offers an incentive to the householder to defer or reduce consumption at times of high system demand. They would also facilitate the roll-out of household micro-generation. It has been estimated that more flexible household supply contracts, facilitated by smart meters, could reduce total electricity consumption in the UK by 2%. Smart meters that can do this already exist and some are already cost effective. Italy will have replaced all its 30 million household meters with smart meters by the end of 2005. Based on interviews with industry participants, the chapter highlights the need to provide incentives for the adoption of smart metering in the UK, it suggests that under the current system neither distribution network companies or electricity supply companies have a strong incentive to encourage consumers to install a smart meter.

## 6. Common and contextual factors affecting new technologies

As we noted in the above overview, the new energy technologies exhibit different characteristics such as cost level, scale, underlying technologies, and stage of development and maturity, and diffusion. The future development of these technologies may not only depend on own merits and distinct characteristics. In the long-run, a number of factors exogenous to technology characteristics can be influential in the level of R&D efforts and promotion of new energy technologies.

These issues are explored further in Chapter 2. However, given their importance, we highlight them up front.

***New technologies and electricity market liberalisation***

It is conceivable that much, if not most, of future technical progress in sustainable energy is likely to take place in market-oriented operating environments. The 1990s witnessed the emergence of electricity sector reforms in many countries across the world. The main objective of the reforms has been to improve operational and investment efficiency of the sector through restructuring, competition, regulatory reform, and privatisation. The reforms have taken place within the backdrop of a wider paradigm shift from state ownership and centralised management of infrastructure industries to market-oriented structures, independent regulatory oversight, and private ownership structures (OECD, 2003). Indeed, the main driving forces and mechanisms of liberalisation reform have had little to do with technical progress and promotion of new energy technologies has been on the sidelines (see e.g. Russell and Bunting, 2002). However it is the case that the co-incidental innovation the combined cycle gas turbine plant or CCGT (the low-cost technology of choice in the electricity sector) facilitated competitive entry into liberalised electricity markets (Newbery, 2000). The technology push and market pull policies and instruments to promote new technologies can be regarded as corrective measures and interventions in liberalised sectors in order to correct market failures.

***Energy R&D and technology policies***

It is conceivable that, in time, the current cost band within which the new technologies lie, will gradually become narrower**.** Within this context, the role of technology and market support policies, to the extent that these are not technology-neutral, will be increasingly more important. Most power technologies have enjoyed significant government support (either directly or through non-competitively awarded contracts) at some point during their life cycle. This is even true of CCGTs which were born out of the heavily subsidised and protected aerospace industry. Government support for renewables has been increasing across the IEA countries in recent years and seems set to increase further (IEA, 2004b).

***Fossil fuel prices and security of supply***

The cost of electricity from conventional thermal technologies is dependent on price of fossil fuels. The cost difference of electricity production from conventional relative to new technologies is therefore influenced by long-term trends in fossil fuel markets. Small and medium size combined cycle gas turbines (CCGTs) have been instrumental in the development of liberalised electricity markets. The price of natural gas is closely linked to price of crude oil in European markets. It is conceivable that economies of scale and technological progress in the medium-term will lower the cost of transporting liquefied natural gas (LNG). A move to increased LNG trading will result in a larger and more competitive international market for natural gas that is more correlated with the volatile oil market. To the extent that such market integration reduces prices it will make renewables less attractive. However, to the extent that it makes gas and oil prices move together it will increase the value of renewables within a portfolio of electricity generation (Awerbuch, 2003). A sustained increase in the price of fossil fuels combined with uncertainty over their supplies will lead to an increase in R&D efforts and faster adoption of new energy technologies. The new technologies with a cost advantage and an option value are likely to attract more support.

***Macro-economic factors***

Generally, a high-growth economic environment can lead to higher spending on and promotion of new technologies. The new energy technologies tend to be more capital intensive than conventional energy technologies. Although, cost reductions may reduce capital intensity of these technologies, they are likely to retain this characteristic for the foreseeable future. The price of capital will therefore be a crucial factor affecting the cost, development, and competitiveness of new technologies. High interest rates will push up the cost of new energy technologies disproportionately relative to conventional technologies. In an economic environment with sustained high-interest levels, the cost of investments in capital intensive technologies and promotional subsidies to support them will increase. Moreover, if the competitiveness of capital intensive technologies diminishes it can result in less R&D spending in these technologies. The 1970s can be viewed as a period of low real interest periods while the most recent years may be characterised as periods of relatively high real interest rates. The extent to which high energy prices cause structural changes in the economy or effect national competitiveness will be important in either encouraging investment in renewables (if oil and gas prices are high) or discouraging investment in renewables (if their relative cost is seen to be high).

***Public acceptance***

In the coming years, a range of issues such as environmental and climate change concerns, security of supply, and performance of liberalised markets are likely to engage public opinion and interest groups in energy and technology policy. Public perception of these issues can lead to demands for limiting certain conventional sources of electricity and/or promoting new and emerging technologies. Public acceptance is instrumental in the adoption and success of policies towards new energy technologies. So long as new technologies cannot compete directly with conventional sources, public acceptance will play an important role in maintaining market support mechanisms and policies favouring new technologies. Ultimately, large scale deployment of renewable energy sources through market instruments and institutional frameworks will largely depend on the extent to which the expressed public support will also translate into support for the development of actual projects (Wolsink, 2000).

## 7. Concluding observations

In closing we make a number of observations based on the chapters.

First, the technologies we include are not comprehensive. For instance, we do not discuss nuclear fusion, tidal or geothermal technologies. This is because the technologies we do consider are those likely to reach maturity in the next three decades and which are capable of making a significant global contribution on such a timescale.

Second, conventional technologies such as coal and nuclear are likely to be significant for some time to come. This makes support for ‘clean’ conventional technologies (carbon capture and new forms of nuclear) potentially attractive.

Third, renewables pose significant environmental and siting problems of their own. These relate to the difficulty of obtaining suitable sites with appropriate levels of local support both for generation, storage and transmission technologies. Careful siting is required as well as innovation in minimising the visual impact.

Fourth, technology does offer the prospect of lower demand for energy via reduced system losses and industrial, commercial and residential demand. This is clearly significant in reducing requirements for new generation capacity. It may be that support for this aspect of carbon reduction may be very cost effective in the short term.

Fifth, there is widespread agreement that almost all of the new technologies that we discuss are still reliant on government funding support mechanisms. For some the required outlay will initially be modest as they are at the fundamental design stage (such as wave). However for some of the close to maturity technologies (such as wind) the subsidies are financially very significant due to the large amount of installed capacity.

Sixth, renewables require a range of support policies. These include a favourable price for renewable electricity generation but also direct subsidy of particular technologies at early stages of development. In the UK technology neutral price-support mechanisms have been less effective than policies in other countries in encouraging either the quantity or diversity of renewable generation.

Seventh, none of our authors suggests that their technology is the only one that should be used to address the carbon reduction targets set for the electricity sector. It is clear from the range of potential technology options and their associated limitations (e.g. in terms of maximum potential capacity) and risks that the encouragement of a diversity of technological approaches is desirable.

In closing it is important to note that any view of the future can only 'look through a glass darkly'. Technological change cannot be clearly anticipated. This is particularly true in the area of climate change. New information about the future effects of climate change and the possibly severe nature of the effects themselves may substantially impact on the technologies we discuss. Events may also provide impetus to even newer technologies before 2050.

## References


Awerbuch, S. (2003). Determining the real cost: Why renewable power is more cost-competitive than previously believed, Renewable Energy World, March-April.

DEFRA (2005). e-Digest of Environmental Statistics, March, London: Department of Environment, Food, and Rural Affairs.

DTI (2003). Our Energy Future - creating a lowcarbon economy, Cm5761, London: The Stationery Office.

EEA (2004). Energy Subsidies in the European Union: A Brief Overview, EEA Technical Report 1/2004, Copenhagen: European Environment Agency.

European Commission (2004). Electricity from Renewable Energy Sources, Brussels: European Commission, Directorate-General for Energy and Transport.

IEA (2004a). World Energy Outlook 2004, Paris: International Energy Agency.

IEA (2004b). Renewable Energy: Market & Policy Trends in IEA Countries, Paris: International Energy Agency.

IEA (2003). World Energy Investment Outlook 2003, Paris: International Energy Agency.

National Audit Office (2005), Renewable Energy, HC 210 Session 2004-2005, 11 February 2005, London: The Stationery Office.

Newbery, D.M.G. (2000), Privatization, Restructuring and Regulation of Network Utilities, Cambridge, MA: MIT Press.

OECD (2003). Environmentally Harmful Subsidies Policy Issues and Challenges, Paris: Organisation for Economic Co-operation and Development.

Russell, S. and Bunting, A. (2002). Privatisation, electricity markets and renewable energy technologies, in Jamison, A. and Rohracher, H. (eds.), Technology Studies and Sustainable Development, Munchen and Wien: Profil Verlag.

Wolsnik, M. (2000). Wind Power and the NIMBY-Myth: Institutional Capacity and the Limited Significance of Public Support, Renewable Energy, 21(1):49-64.

World Commission on Environment and Development (1987), *Our Common Future*, Oxford: Oxford University Press.