Imperial College Centre for Energy Policy and Technology

Assessment of Technological Options to Address Climate Change

A Report for the Prime Minister's Strategy Unit

December 20, 2002

Note: This report was commissioned by the UK Government as a piece of independent research and is being circulated to inform and stimulate debate. The report is not a statement of the UK's government policy.

Contents

Preface

This report was produced in October 2002 at the request of the Prime Minister's Strategy Unit. It aims to analyse the potential of low carbon technologies for delivering deep cuts in greenhouse gas emissions worldwide by 2050. The terms of reference requested information on:

- The likely quantitative contribution of the various technologies and their costs
- Key obstacles to uptake
- Which technologies are best suited for different parts of the world, with reference to the OECD economies, Russia, Asia, Africa and developing regions
- The technologies with the greatest potential
- Factors that would affect the adoption of the technologies identified
- Implications for economic growth
- Challenges ahead and suggested further actions

The report shows why the climate change problem could be addressed through both national and international commitments to the development and use of low carbon technologies and practices – defined here as technologies and practices that avoid or reduce net emissions of CO_2 to the atmosphere. It reviews why numerous studies have concluded that countries can aspire to achieving economic prosperity on a broad basis, and the OECD countries to raising their economic livelihoods further, while addressing the climate change problem.

The report has benefited from comments on early drafts from experts from industry, government and academia. In addition, a workshop on regional aspects was convened by the Carbon Trust on 29th October 2002, and an expert workshop was run by the Strategy Unit on 1 November. Persons consulted are listed at the end of the document, as are the main contributors from Imperial College London, Warwick University Business School, Future Energy Solutions and NERA. We have also benefited from ongoing work at the Department of Trade and Industry on UK energy policies. We are immensely grateful to all involved for their time and expertise.

The report cannot do full justice to the enormous range of issues and options involved in rising to the challenge of reducing carbon emissions. Nor can it possibly be encyclopaedic. Any errors or omissions are the responsibility of the authors alone.

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Executive Summary

The challenge

Under existing policies carbon dioxide emissions from energy use will increase substantially over the coming 50 years. The increases will be greatest in the developing countries: their energy consumption per capita is very low compared to that of the industrialised countries, they have 2 billion people without access to modern energy forms, and will need far more energy to achieve economic prosperity.

With economic growth world electricity demand could expand four-fold relative to today's level – equivalent to 10 times the installed capacity in the US, or 120 times that of the UK. World oil consumption would also rise to several times levels found in the US and Europe today, unless alternatives to oil can be found.

But growth in CO_2 emissions is not inevitable. The IPCC reviewed global emissions in 140 scenarios, and industry, international organisations and governments too have published their own analyses, as has the G8 Task Force on Renewable Energy. Their main conclusion is that we could move to a low carbon emissions path, and achieve a virtually zero carbon energy system in the long term, *if* we used energy more efficiently and *if* we developed and used low carbon technologies and practices.

This is technologically and economically feasible. Profound changes occurred in energy production and use in the last 50 years, and profound changes seem equally likely in the years ahead when we examine emerging technologies.

Technology options

Reductions of emissions could be achieved by improving energy efficiency and by using low carbon-emitting energy sources. Fundamental changes in the infrastructure by which energy is supplied and used would also be needed.

Energy efficiency

It is estimated that one-half of future emissions, relative to trends, could be eliminated through efficiency gains, perhaps more with technical progress and if the uptake of technologies is encouraged through energy policies. Examples of options already available abound in building design, appliances, lighting technologies and transport. But the possibilities for further improvement through innovation are far from exhausted. For example, transport accounts for around ¼ of CO_2 emissions, and for the bulk of the 3.5 billion tonnes of oil consumed in the world today. The 'well to wheels' efficiency of vehicles is 15%; new technologies such as fuel cell and hybrid-electric vehicles would double this.

The use of natural gas will also be associated with large gains in energy efficiency, and is the 'fuel of choice' for power generation and heating in homes and industry for those countries with good access to it. It would reduce CO_2 emissions directly given the lower carbon content of gas relative to oil and coal, and it has several other environmental advantages. But given the dependence of large countries such as India and China on coal, and their more limited access to gas, high efficiency coal technologies will also be important; those based on coal gasification may open up a path towards hydrogen production (see below).

Low carbon energy sources

There are three main options: renewable energy, nuclear energy, and fossil fuels with the carbon being separated out and sequestered.

Renewable energy

The resource is very large. For example, solar energy alone could meet world energy demand using less than 1% of land now under crops and pasture. Of course there is no need to occupy such land, since deserts and rooftops can be used for solar technologies, and several other options show great promise—wind, tidal stream, wave, geothermal energy. Biomass energy can be derived from agricultural and forest wastes, and biomass plantations can also be used to help restore degraded land and watersheds.

Most of the technologies are technologically viable and many are well proven, but with exceptions their costs are high relative to fossil fuels. However, cost trends are encouraging; for example the cost of wind has fallen fourfold since the mid 1980s. Most technologies are in their infancy and there is appreciable potential for further reductions through innovation and batch production.

The issue of intermittency will need to be addressed if the solar and wind technologies are to provide energy on the scale required. This will require the development of storage technologies, such as hydrogen, and changes to the way power grids are operated.

Nuclear energy

Nuclear fission is a familiar and well tested option; it accounts for 7% of the world's primary energy production and 17% of its electricity production. We now have more than 40 years of operating experience with the technology. New smaller reactors, with improved safety characteristics are now being developed. The difficulties with its wider scale deployment in response to the climate change problem lie as much with the much-discussed and unresolved issues of nuclear wastes, safety, decommissioning and proliferation, as with reactor size and efficiency. For these reasons many of the studies reviewed here assign to it a secondary role or conclude that it cannot be relied upon for achieving major reductions in carbon emissions over the long term.

Nuclear fusion is thought unlikely to be available commercially for 25 or probably 50 years.

Hydrogen production from fossil fuels with carbon sequestration

It is possible to separate out the CO_2 from fossil fuels for geological storage in depleted oil or gas reservoirs, coal beds (for enhanced methane recovery) or deep saline aquifers. Doing so is a promising way to make hydrogen. These possibilities are attracting much interest since they would open up another route for the fossil fuel industry to continue to supply electricity generation and transport. The potential for sequestration is large – perhaps as much as 50 years of current global emissions. It may be much larger, but we need more research on the various reservoirs. CO_2

storage is likely to increase the cost of using fossil fuel by around 30% once the technologies are proven.

Energy infrastructures: changing the way energy is supplied
Aside from innovations in the component technologies, there will need to be major changes in the infrastructures for supplying energy. Some of the most promising technologies offer the possibilities for decentralised generation on a small scale, for example fuel cells for combined heat and power, and solar PV; there could then be literally millions of small scale generating sets on electricity grids, and millions of consumers becoming independent of the grids. Hydrogen production and distribution for electricity generation and transport would also require us to evolve a new infrastructure. The scale and complexity of the transformation should not be understated, and it could not be embarked upon without a long-term commitment from industry, supported by public policies and the research community.

Conclusions

1. Cutting CO_2 emissions. Substantial cuts in emissions from energy production and use could be achieved over the coming decades. The situation differs between the industrialised and the developing countries – in the latter emissions will inevitably grow before they could be reduced. In the longer term, the world can aspire to meeting its growing energy needs with very low greenhouse gas emissions.

2. *The technological options*. Currently the most promising options are: (a) The full range of renewable energy technologies—wind, biomass, solar, geothermal, wave and tidal stream technologies. (b) Efficiency in energy production, conversion and use. (c) Hydrogen for transport and electricity generation. The use of fossil fuels to produce electricity and hydrogen with the CO_2 being sequestered could also prove to be important as a transitional option. Nuclear power remains a possibility if a solution to the waste problem is found, and if new and better nuclear technologies can be developed that prove publicly acceptable.

The actual mix of technologies that it is desirable to deploy within these categories will vary between countries. There is no panacea, and we have argued for a broad portfolio of investments in these areas.

3. *Costs and policies*. The private or 'market' costs of the low carbon options are higher than those of fossil fuels. In addition, there will be the huge task of transforming energy infrastructures to accommodate the new technologies. Industry will not be able to do this without a supportive regulatory framework and policy commitments from governments.

A research and demonstration effort will also be required at national and international levels to take the emerging technologies forward. This is fertile ground, and R&D will yield significant improvements over time. Research on policies and into the acceptability to the public of the new technologies will also be needed for defining a socially acceptable path ahead.

4. *Living Standards and Development.* The impacts on economic growth and development are likely to be very small – roughly equivalent to a loss of 6 months

growth over 50 years. In other words people living in 2050 would have to wait 6 months or so for their incomes to rise to what they would have been in the absence of policies to address climate change. This is large in absolute terms but small in relation to incomes, which could be up to three times larger by then. In addition, such calculations ignore the benefits of environmental improvement, and in this respect overstate the net costs. More generally, there is no reason why the world cannot aspire to achieving economic prosperity on a broad basis in a low carbon future.

5. *A New International Initiative?* We have a unique opportunity to address the problem of climate change by supporting innovation at the international as well as national level. Governments around the world, including all countries in the OECD, and a large number of developing countries, are inching their way toward such policies. We have suggested that:

- Making commitments to innovation in low carbon technologies would introduce a creative new element to the international dialogue on policies for addressing climate change.
- Such commitments would be ideally complemented by a new international institutional arrangement and funding mechanisms for advancing innovative technologies in the areas of renewable energy, energy efficiency and hydrogen production and use.

The experience of the Global Environment Facility with investments under the UN Framework Convention on Climate Change shows that funding mechanisms can achieve appreciable financial leverage in practice. Funds could be levered from the private financial sector and industry, and from the resources that would be generated by a supportive policy environment.

In the past decade we have seen appreciable progress in the technologies discussed and in our understanding of how energy systems might evolve. New institutional arrangements are beginning to emerge at the national and international levels, and governments and the research community are in the throes of seeing what can be learned from previous policies. There is an excellent foundation to build on.

Part I

Overview and Main Findings

Part I. Overview and Main Findings

1. Introduction

Climate change is among the most daunting environmental problems faced by the world today. The Third Assessment Reports of the IPCC (2001) have shown that the consequences for human activities and the environment will be far reaching and profound, and that no region of the world will be unaffected.

It is encouraging therefore that numerous studies have shown that major cuts in emissions of greenhouse gases could be achieved over the coming decades without damaging the economic prospects of either industrialised or developing countries. While often differing in detail and in assumptions, one over-riding conclusion emerges: *innovation* will be central to addressing climate change, through the development and use of low carbon[1] technologies. Furthermore, this would be consistent with the goals of the world achieving economic prosperity on a broad basis, together with secure energy supplies and a better environment. On the other hand, most low carbon options are in their infancy and considerable investments will be required if they are to develop, while others (notably some renewable energy and energy efficient technologies) are already available but lack the policy and regulatory stimuli required for their uptake. There is therefore a major task ahead for both the industrialised and the developing countries alike, and also for international institutions and leaders, to find ways of fostering the development and use of low carbon options.

This report provides an overview of the technologies; their current and expected costs, their potential for addressing the problem of climate change and their prospects in the near and long-term. It then discusses the challenges ahead in developing the technologies and in stimulating further innovation and use.

The report suggests that while many industrialised and developing countries are beginning to put policies in place to encourage innovation, there is a need for a new initiative at the international level to foster innovation in response to the problems posed by climate change.

It begins with background material on why it has been widely concluded that, through innovation and the policies that support it, we can reconcile the task of addressing the environmental problems arising from energy production and use with the broader goals of development.

[1] We use ‘low carbon’ throughout this report as shorthand for all options that reduce net carbon emissions to the atmosphere.

2. The Scale of the Challenge and the Role of Technology

2.1 Energy needs: the contrasting situations of OECD and developing countries

Despite a 10-fold expansion of world energy consumption in the 20th century, all the evidence points to continuing expansion in the present century. The explanation lies in part in the growing weight of developing countries in world energy markets. Energy markets in the OECD countries, which accounted for the bulk of growth in the last century, are maturing and the growth of energy use is slowing down except in some electricity markets. But this is not true of South and East Asia, Africa and Latin America, where all energy markets are far from saturated and growth rates are three times higher than those of the OECD.

Per capita energy consumption in low and middle-income countries is barely one sixth of that of the industrialised countries, and oil consumption one tenth, as table 2.1 indicates. Two billion people are without access to modern energy forms, populations are set to increase by another 3-4 billion people, and energy demands are growing very rapidly. If developing countries are to achieve prosperity large expansions of energy supplies will be necessary; no country has been able to raise its per capita incomes from low levels without increasing its use of commercial energy.

Table 2.1: Populations, income and energy consumption c2000

Quantity	Low and Middle Income Countries	High Income Countries
Population, millions	5,200	900
Gross National Income, $ billions	6,300	25,000
Per Capita Incomes, $	1,250	26,000
Energy Use:		
Total energy use, million tonnes of oil equivalent	4800	4900
Oil consumption, tonnes per capita	0.25	2.4
Average electricity consumption, kWh per capita	1,200	9,800
People without access to electricity, millions (in 1996)	2,000	-
Increase in energy demand per decade (1990s)	70 %	20 %
CO_2 emissions from commercial energy use, tonnes per capita	2.3	12.6

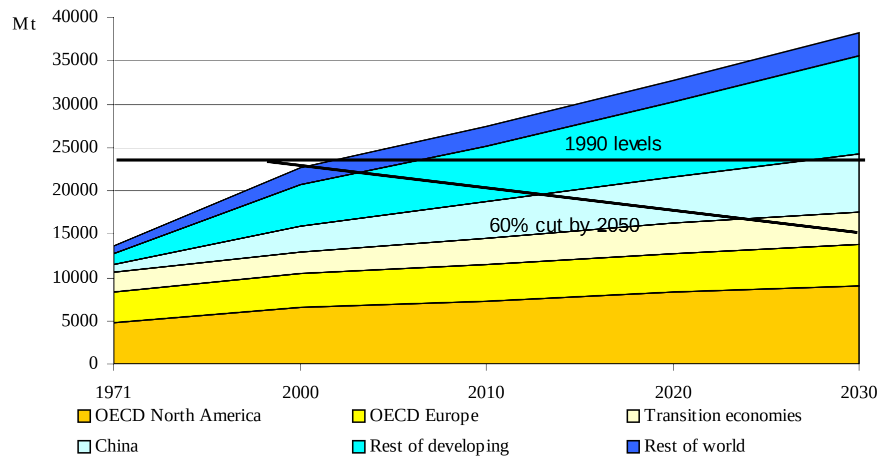
Source: World Development Report, World Bank (2000), except for oil, which are from the *BP Statistical Review of World Energy*. Estimates rounded. Low and middle-income countries here include economies in transition, including the former Soviet Union and Eastern Europe, which have relatively high levels of energy consumption.

Estimates of the precise magnitude of the expected expansion vary. But assuming reasonable improvements in energy efficiency, per capita energy consumption of low and middle-income countries might approach saturation at roughly half of that of the OECD countries today. This would require around 8 million MW of new electricity generating capacity – over ten times that installed in the United States and 120 times the capacity installed in the UK or France, for example. Their oil consumption would also rise, unless some alternative to oil is found, from 1.2 billion tonnes today, to over 10 billion tonnes – over seven times the combined consumption of the United States and Europe today.

Overall, emissions in developing regions could become three or four times greater than those of the OECD countries today, and without development and use of low carbon technologies, global CO_2 emissions will grow several fold in the next 50 years. Such estimates indicate the magnitude of the task of addressing the problem of climate change whilst developing regions achieve economic prosperity.

Figure 2.1 shows the IEA's 'reference' (business as usual) scenario of growth in CO_2 emissions across the different regions of the world without policy intervention and technology shifts.

Figure 2.1: Scenario of growth in CO_2 global emissions by region (IEA reference case)

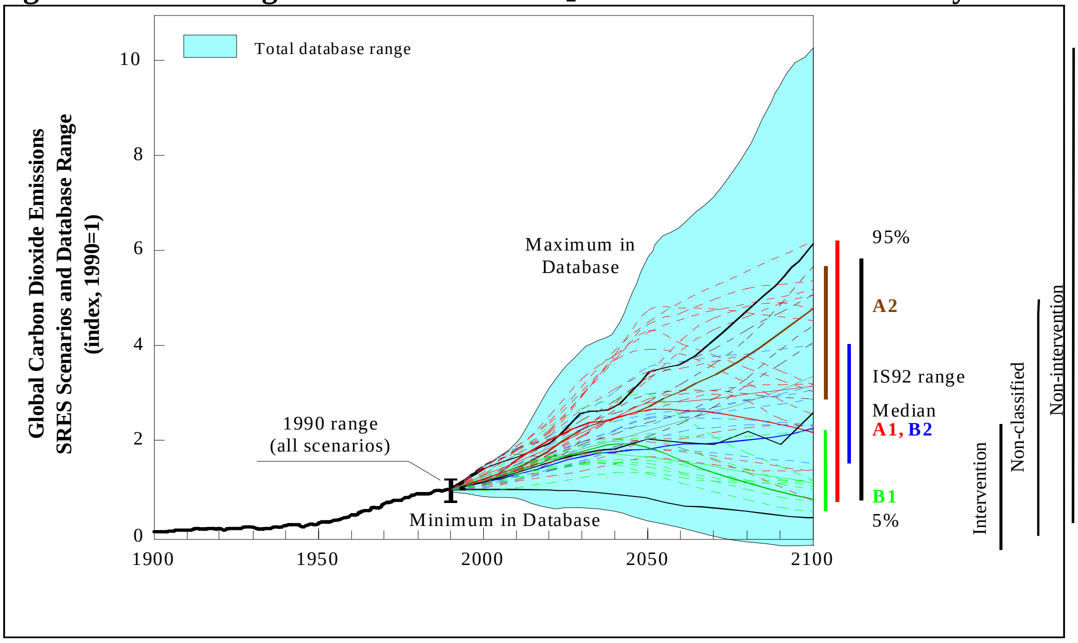


source: World Energy Outlook 2002, IEA

Yet both industry and research community scenarios suggest that it is possible (though the outcome is far from inevitable) to combine environmental improvement with an expansion of commercial energy use.[2] Figure 2.2 shows the range of CO_2 scenarios reviewed by the IPCC. In some cases CO_2 emissions are seen to rise exponentially to 10 or more times today's levels; others conclude that a stabilisation and then a reduction of emissions to below today's levels or zero is possible over the long-term.

[2] A comprehensive review is provided in the *Special Report on Emission Scenarios* for Working Group III of the IPCC in 2000, Cambridge University Press, which reports the results of over 140 peer-reviewed studies. Earlier surveys had come to the same conclusion, e.g M Grubb, J Edmunds, P ten Brink and M Morrison (1993) "The costs of limiting fossil-fuel CO2 emissions: a survey and analysis." *Annual Review of Energy and the Environment*, 18:397-478. The Shell scenario shown in Figure 3.1 below also assumes continued world economic growth, as did the World Bank's 1992 World Development Report. The G8 Renewable Energy Task Force (July 2001) also showed the importance of new renewable energy and energy efficient technologies for mitigating climate change.

Figure 2.2: The range of scenarios for CO_2 emissions in the 21st century



Source: IPCC 2000

What explains such disparate estimates? The high emission scenarios assume continued and expanding use of fossil fuels, particularly coal. The low emission scenarios, in contrast, all assume a long-term transition to low carbon energy forms, and a growth in energy efficiency. In other words, the key to reducing emissions is the development and adoption of low carbon technology.

2.3 The Role of Technology

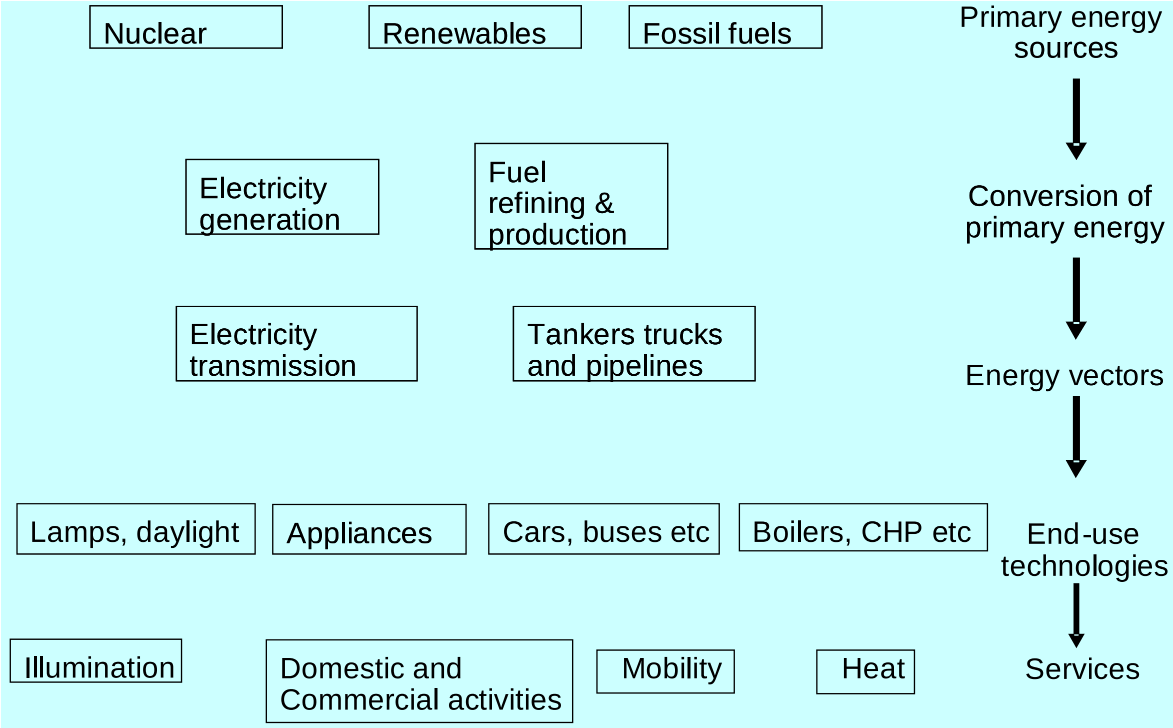
Most environmental problems associated with energy production and use in the past have been successfully addressed, with emissions and impacts eliminated or substantially reduced. In almost every case the development of low-emission technologies and practices was the reason, usually with the incentive of environmental policies. Examples include the reduction of acid-rain causing gases from power stations and harmful emissions from vehicle exhausts, and the elimination of wintertime urban smog in the richer countries.

The costs, often thought to be prohibitive when the policies were being introduced, generally turned out to be low as a percentage of energy supply or user costs—typically 2-3%—and sometimes negative, as when natural gas was substituted for coal as a domestic and industrial fuel. In fact, no environmental problem associated with energy use has so far proven to be too economically disruptive to address. There is also much evidence that, once the economic benefits of a cleaner environment and improved efficiency are taken into account, economies have found themselves better off as a result of effective environmental policies and the innovations they brought about.

It will prove to be more difficult to reduce the emissions of greenhouse gases as a result of burning fossil fuels, as carbon is inherent in all fossil fuels and they provide around 90% of primary energy. Nevertheless, as the studies just cited have shown, deep cuts in the amount of CO_2 associated with delivering the 'energy services' that people want – heat, light, electricity and motive power – are perfectly feasible technologically.

Emission reduction is possible at each stage of the 'energy chain' linking primary energy sources to end uses, a version of which is illustrated in Figure 2.3 below.

Figure 2.3: The 'Energy Chain'



Carbon emissions can be reduced in each link of the energy chain, through:

- Technologies to exploit low carbon primary sources such as renewables and nuclear power, or avoid CO_2 emissions from fossil fuels escaping into the atmosphere;
- Improved efficiency in conversion of primary energy;
- Improved efficiency in the transport and transmission of energy, and the introduction of new energy vectors such as hydrogen;
- Improved efficiency in end use technologies.

Low carbon technologies and practices in each of these stages are summarised below, with more details provided in Part 2.

Leading energy companies are engaged in the development of low carbon options. The development of renewable energy is attracting the attention of large energy, and manufacturing companies, and new specialist companies have emerged. Leading car manufacturers are also investing in the development of 'zero emission' fuel cell and high efficiency 'hybrid' vehicles (see Box 2.1).

This is not surprising. The future has never been 'more of the same' in energy as in other industries; continual and often profound change has occurred over the past two centuries. First there was the substitution of coal and steam power for wood fuels, then the emergence of the electricity industry, hydro-electricity, oil, gas and, since the 1950s, nuclear power and high efficiency gas turbines. More recently we have seen the emergence of modern renewable energy forms. These changes coincided with an ever-expanding array of applications and with order-of-magnitude improvements in the efficiency with which energy is converted and used.

Box 2.1: Private sector engagement in low carbon technologies

Economic incentives and environmental policies are leading to increasing investment by the private sector in low carbon technologies. The main activities are in renewable energy, CHP and fuel cells, advanced fossil technologies and carbon sequestration, hydrogen, vehicles and end use efficiency. Some of the main players include:

- *Specialist firms* It is impossible to list them all the number is very large. Examples in the wind sector are Vestas, Enercon, Nordex, NEG Micon, Bonus. In photoltaics the catalogue of companies engaged amounts to several hundreds.
- *Research based spin outs from universities*—Ballard, leading developers of fuel cells and Wavegen, developers of wave power systems.
- *Large energy and engineering companies*. These are entering in the field through specialist subsidiaries, acquisitions or in-house R&D. Examples include: PV – BP, Shell, Siemens; wind power – General Electric, Shell, ABB; fuel cells – Alstom, Rolls Royce, Johnson Matthey; carbon sequestration – BP, BOC, Exxon. The field is expanding: for example UK-Dutch steel maker, Corus, recently unveiled an innovative tower/foundation for offshore wind.
- Most of the *leading car makers* are investing in low emission vehicles – Ford, GM, Daimler Chrysler, BMW, Honda, Toyota, Renault-Nissan Alliance and PSA Peugeot Citroen.
- *Electricity supply companies and utilities* are moving into renewables development and operation – examples include Texas Utilities, Powergen, Innogy, Elstom
- *State owned or recently privatised nuclear industries.* These are the main companies active in new nuclear technologies – BNFL Westinghouse, Candu and Eskom are examples, though General Electric and Siemens retain an interest in nuclear technologies.

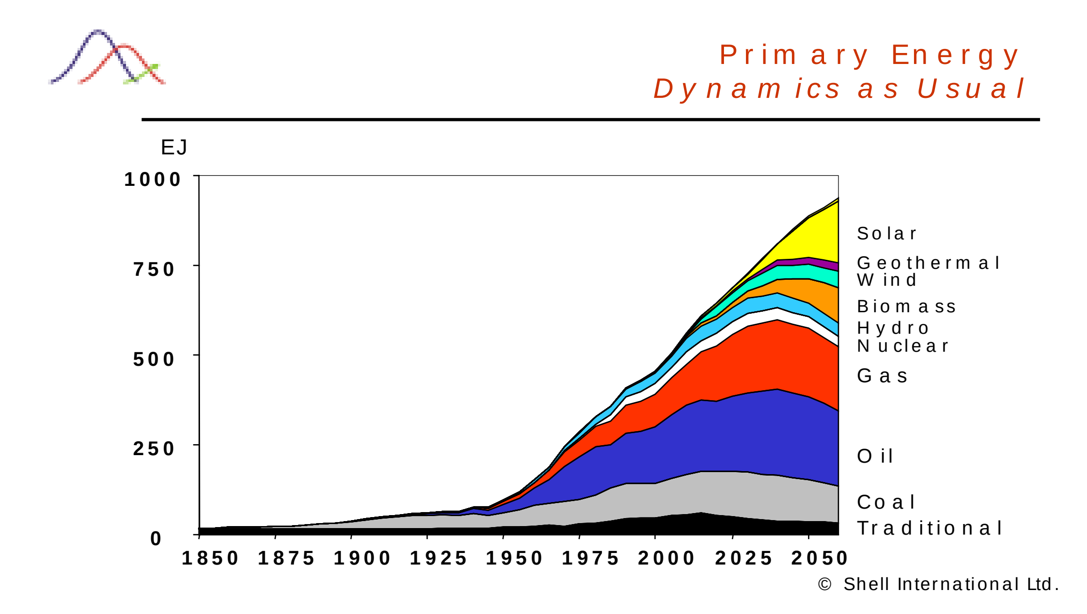
There is no commercial interest in nuclear fusion.

3. Technology Options: A Summary

3.1 A Global View

Studies by industry and the international research community point to an increasing diversity in the sources of future energy supply, with renewable energy occupying a rising share. The Shell scenarios capture this very well (Figure 3.1), and echo the findings of the IPCC, World Bank, World Energy Council and others. As will be seen there is also a diversity of options on the demand side—for meeting energy people's energy needs more efficiently—without which future world energy demands would be much higher than are illustrated in this scenario

Figure 3.1: A Scenario of the Royal Dutch Shell Group[3]



As the chart suggests, the transitions from one energy form to another take place over long time periods. Abrupt changes are not possible, and in the meantime energy demands have to be met—not least to improve livelihoods and avoid social disruption. Energy infrastructures are large, complex and long-lived, as are the equipment, appliances and vehicles that are tied into existing forms of supply. Hence the use of existing technologies and fuels persists, and in growing markets may expand rapidly even as new technologies are emerging on the scene. In addition, it takes time to develop, prove and improve the efficiencies and reduce the costs of the new technologies, which may further limit the rate of uptake.

In these circumstances it is obviously desirable to put resources into improving and reducing the environmental impact of the use of the fuels that will continue to supply most of the market for several decades. Hence the rising importance of natural gas in the above chart, and also (not shown explicitly) of end use efficiency, cleaner vehicle

[3] Note: an exajoule (the unit on the vertical scale) is a unit of energy equal to 10^{18} watt seconds or approximately 280 billion kWh. World energy demand today is approaching 400 exajoules. We are grateful to Ged Davis of Shell for providing us with this chart.

fuels and cleaner technologies for burning coal. Nevertheless, we also need to consider the alternatives if the climate change problem is to be addressed.

Part II of this report provides a non-technical assessment of several of the most important options, drawing on the studies of business and the research community. The range of possibilities is large, and can be classified under three headings: energy efficiency, low carbon primary energy resources, and new energy systems and facilitating technologies.

3.2 Reducing primary energy demand through greater efficiency: Improving efficiency in energy conversion, transportation and use

By this we mean obtaining the lighting, heating, cooling, motive power, transport and other uses for which people require energy while using *less* energy—more fuel efficient transport and lighting, for example. Energy efficiency has led to large savings in the past. Electric power stations operated at efficiencies of barely 5% at the turn of the 20th century, and generated approximately 400 kWh/ton of coal; today they generate nearly ten times this amount per ton. Modern fluorescent lighting is 700 times more efficient than the kerosene lamp that meets the lighting needs of hundreds of millions of people in developing countries today. The last century has seen a 50 fold improvement in the efficiency of illumination devices, with a significant improvement in lighting quality. There is scope for developing countries to move straight to more efficient options as demand for lighting expands, indeed many already manufacture modern discharge lamp technology. New technology based around the light emitting diode could improve efficiency further and reduce costs.

There are many other examples. In all aspects of energy production and use—in air and surface transport, in homes, industry and commerce—examples of major improvements over the last two centuries abound. In some instances gains in efficiency, by reducing costs, can be a stimulus to further use, but the overall effect has been to reduce energy demand relative to what it would have been without the improvements.

All the available analysis shows that the scope for further gains in efficiency is far from exhausted. For example:

Energy efficiency in buildings: Energy use in buildings accounts for about one-third of all energy use. Many cost effective improvements are available now; the extent to which these are adopted varies by country and improving adoption of existing best practice is important for reducing emissions in the short term. Areas where innovation can foster further improvements include heating and cooling technologies; lighting; building envelope and architectural improvements; building energy management systems; small scale combined heat and power (CHP) and heat pumps. Developing countries are especially well-placed to benefit from such innovations in the next 50 years because of the high proportion of investment that will go into new buildings.

Energy efficiency in industry: Numerous areas hold scope for improvement. Some of the most spectacular productivity improvements in primary energy use over the last decades have been in the process industries where an engineering technique sometimes called ‘process integration’ has been applied to multi-stage processes. This explores the options for using the waste products and heat from each stage as an input for another step in the total process. Analysis suggests that if applied to an industrial economy as a whole, this technique could save something like 30% of primary energy consumption without any change in end use technologies. The use of waste heat from power stations in CHP generation technology, that enables waste heat from power generation to be used in other activities nearby, is a commonplace example of the approach. It raises the overall efficiency of primary energy use to around 80%.

New process plant design exploits process integration techniques to the full, often saving 30-40% of energy over non-integrated processes.

Transport efficiency improvements: Major efficiency improvements and emissions reductions are feasible through advanced chassis, lightweight materials and fuel cell and hybrid (petrol- and diesel-electric) propulsion in vehicles. Congestion management systems and, of course, urban development policies are also central.

Efficiency improvements in electricity supplies from 'clean' fossil fuels: these include improvements in transmission, advanced electricity generation technologies, loss reduction through fuel cells and micro-turbines for decentralised sources of CHP.

It is estimated that roughly one third to one half of reductions in future emissions, relative to historical trends, could arise from further efficiency improvements (World Energy Assessment, 2000 and the IPCC Special Report on Emission Scenarios, 2000).

3.3 Low carbon primary energy resources

The main resources are renewable energy, nuclear power and the use of fossil fuels with the CO_2 emissions being sequestered geologically.

Renewable energy: There are several renewable technologies which could contribute to a low carbon future: solar-photovoltaic devices both for off grid and grid-connected energy supplies; solar-water heaters; low temperature solar heat for industry and commerce; high temperature solar concentrators for power generation and desalination; biomass (from crops and residues); onshore and offshore wind; energy from tidal streams and waves; hybrid wind-wave or wind-tidal stream devices; and geothermal energy.

All are proven technologies, with the partial exceptions of wave and tidal stream devices. Under incentives provided by governments in all OECD countries, and an increasing number of developing countries, including China, India, Brazil, and many others, investment and operating experience is rapidly being built up. The Global Environment Facility (the financing arm of the UN Framework Conventions on Climate Change and Biodiversity) has a diverse portfolio of renewable energy projects in 70 countries.

The land requirements of renewable energy are not—or should not be—an issue. For example, a measure of the yield of renewable energy per unit area is the amount of oil that would be needed to supply the same amount of useful energy (e.g. in kWh). On this basis a solar farm would yield nearly 1000 tonnes of oil equivalent per hectare in the tropics, and 300 tonnes per hectare in northern climates such as the UK—a 10-50 fold increase in the effective yield of land relative to crops. In theory, less than 1% of the land now under crops and pasture worldwide would be needed to meet the world's energy demands from solar energy. Of course, there is no need to occupy such lands—desert areas and rooftops are ideal for the exploitation of the solar resource. Nor do we have to rely on direct solar energy alone; other renewable energy technologies have considerable potential, including wind, wave and tidal stream devices. Biomass projects have the additional advantages that they can be designed to restore degraded lands and watersheds and increase the yield of agriculture, in addition to supplying energy; they are also a well tested option for combined heat and power using forest and agricultural residues.

Table 3.1 provides an indication of what renewable energy sources are capable of supplying. It is not possible to provide meaningful detailed quantification, allowing for costs, physical accessibility and other factors. But there is no doubt that the resources, taken together, could meet world energy demands several times over.

Table 3.1: Renewable energy potentials

Resource	Technical potential (energy that could be delivered annually)	Energy conversion options
Direct solar	Much larger than world primary energy demand	Photovoltaics Solar thermal power generation Solar water heaters
Wind	Large in relation to world electricity demand	Large scale power generation on and offshore; small scale generation; pumps
Wave	Not fully assessed but very large theoretical resource	Numerous designs
Tidal	Limited assessment but large	Barrage Tidal stream
Geothermal	Several orders larger than current energy demand. As with other technologies, use depends on costs not the quantity of resource technically available	Hot dry rock, hydrothermal, geopressed, magma (only hydrothermal currently viable)
Biomass	Potential varies greatly between countries, but could meet a substantial fraction of world energy demand and can complement agriculture and protect watersheds and biodiversity.	Combustion, gasification, pyrolysis, digestion, for bio-fuels, heat and electricity

To sum up, renewable energy is abundant and there are many promising options for converting it into useful energy. It does, however, face two difficulties, both resolvable. One is that the intermittent nature of some options would require changes to the management of electricity grids, and development storage and other technologies, as the share of renewable energy on the grid systems rises (see below); the other is the high cost of most options and applications relative to fossil fuels.

Table 3.2 summarizes the cost data collated in Part II. Included in this table for comparison are the costs of fossil fuels and nuclear power[4].

[4] For PV we have also compared the costs with (a) the average retail costs of electricity, since it provides distributed generation, thus avoiding capital expenditures and losses in transmission and distribution, and (b) with those of rural electrification from the grid in developing countries, since 'off-

Table 3.2: The average costs of renewable energy compared with fossil fuels and nuclear power: today and in prospect.

Technology	**Current cost (US Cents/kWh)**	**Projected future costs beyond 2020 as the technology matures (US Cents/kWh)**
Biomass Energy:		
• Electricity	5-15	4-10
• Heat	1-5	1-5
• Ethanol for vehicle fuels	3-9	2-4
• (c.f. petrol and diesel)	(1.5-2.2)	(1.5-2.2)
Wind Electricity		
• onshore	3 - 5	2-3
• offshore	6 - 10	2-5
Solar Thermal Electricity (insolation of 2500kWh/m^2 per year)	12-18	4-10
Hydro-electricity		
• Large scale	2-8	2-8
• Small scale	4-10	3-10
Geothermal Energy:		
• Electricity	2-10	1-8
• Heat	0.5-5.0	0.5-5.0
Marine Energy:		
• Tidal Barrage (e.g. the proposed Severn Barrage)	12	12
• Tidal Stream	8-15	8-15
• Wave	8-20	5-7
Grid connected photovoltaics, according to incident solar energy ('insolation'):		
• 1000 kWh/m^2 per year (e.g. UK)	50-80	~8
• 1500kWh/m^2 per year (e.g. southern Europe)	30-50	~5
• 2500 kWh/m^2 per year (most developing countries)	20-40	~4
Stand alone systems (including batteries), 2500 kWh/m^2 per year	40-60	~10
Nuclear Power	4-6	3-5
Electricity Grid supplies from fossil fuels (incl. transmission and distribution		Capital cost will come down with technical progress, but many technologies largely mature and may be offset by rising fuel costs
• Off-peak	2-3	
• Peak	15-25	
• Average	8-10	
Rural electrification	25-80	
Costs of Central Grid Supplies, excl. transmission and distribution:		Capital costs will come down with technical progress, but many technologies already mature and may be offset by rising fuel costs
• Natural Gas	2-4	
• Coal	3-5	

Source: Source: World Energy Assessment: Energy and the Challenge of Sustainability. UNDP and World Energy Council (2000) updated and extended based on data gathered for the UK government, PIU (2002), and recent simulation studies undertaken for the UK DTI (forthcoming). The above estimates are based on a discount rate of 10%. The costs of rural electrification are from the World Bank's 1996 report: *Rural Energy and Development: Meeting the Needs of 2 Billion People.*

The costs are expected to decline with R&D, investment and operating experience. To arrive at the lower cost estimates shown in the last column, it is evident that a major effort will be required by industry and the research community over the next 25 years.

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grid' solar supplies are expanding rapidly. It was rightly pointed out to us that these calculations ignore environmental costs and, in the case of PV, architectural value.

The technologies are modular, are fertile ground for discovery and invention, scale economies in batch production have barely been exploited, and there is every reason to believe that costs will decline as projected with supporting public policies.

Nevertheless, and notwithstanding the uncertainties in the above estimates, the costs of the non-carbon options to fossil fuels will, with exceptions, be higher than those of fossil fuels for some time. It is difficult to see how they can be developed therefore without policies which reflect their economic and environmental potential, and provide industry with the necessary financial incentives to take them forward. All the technologies reported have depended on this to date.

Nuclear fission: Nuclear power from fissile materials has been commercially available for around 40 years, and in normal operation gives rise to negligible emissions of radioactivity. However, its development outside East Asia has largely stalled in the last decade.

Nuclear technology for electricity production grew rapidly in a range of industrialised countries from the late 1960s until the early 1990s. Currently it provides 17% of the world's electricity supplies, though the proportions vary widely: 75% in France, 20% in the UK and zero in a number of industrialised countries. The light water reactor emerged as the world's dominant type of nuclear technology, especially the Pressurised Water Reactor (PWR) in its US and Russian forms.

All commercial reactors to date have used uranium as their main (usually only) fuel source. There were fears of uranium shortage in the 1950s and briefly again in the 1970s, which led to the development of the fast breeder reactor. Now however it is known that uranium is an abundant element, cheaply obtainable. Conventional uranium resources will last for many decades at relatively low cost, and much more is likely to be discovered. This and safety concerns (which are more acute than for thermal reactors) led to a scaling back of breeder reactor programmes except in Japan and Russia.[5]

The issues of wastes, decommissioning, liabilities and proliferation have received appreciable coverage in public and private inquiries around the world. The technical issues have been studied extensively, but until they are resolved socially as well as technologically, they are bound to be a bottleneck on the future use of nuclear power.

The electrolytic production of hydrogen from nuclear power has also been seen as a future possibility since the inception of the industry nearly 50 years ago, partly with the idea of supplying the transport markets using the fuel cell or combustion engines, and partly to improve the utilisation of the reactors during peak load periods.

Fusion. Energy from thermonuclear (fusion) reactors has been a great aspiration of scientists since the early experimental reactors of the 1950s, though electricity generation on a significant scale is still to be demonstrated. Aside from offering prospects of virtually unlimited energy, it would be inherently safer than fission, lead

[5] The US is also reconsidering its position.

to appreciably lower problems of wastes and be less likely to lead to proliferation problems.

Fusion is still, however, after 50 years of effort, in the phase of fundamental research. Estimates of when the first commercial reactors will be available range from 25-50 years. There has for some time been a proposal for a large International Thermonuclear Experimental Reactor (ITER), based on magnetic confinement of the plasmas, which is estimated to cost US $6bn at 1989 prices (and substantially more at today's price levels). It is intended to be a joint Europe/Canada/Russia/Japan project. Once ITER is built, a further demonstration stage would be needed ('DEMO') before commercialisation could be considered. There are also smaller scale experiments with alternative devices to magnetic confinement, which are generally at the more fundamental research stage.

Carbon separation and storage: This involves capturing CO_2 from point sources such as power stations and oil refineries and injecting it into subsurface repositories such as depleted oil and gas reservoirs and deep saline aquifers. Sequestration in coal beds for enhanced methane recovery is another option. Others being investigated include deep ocean storage; however, the large uncertainties in its prospects have led to a greater focus on geological storage.

Industry estimates suggest that, once technologies are in widespread use, separation and storage would increase the costs of electricity generation from fossil fuels by about one third. Separation represents the most significant part of the overall cost. There is cost reduction potential as technology develops and experience is gained.

Sequestration in depleted oil and gas fields is thought to be a secure option if the original reservoir pressure is not exceeded. Estimates of the prospective global sequestering capacity of such reservoirs associated with past production plus proven reserves plus estimated undiscovered conventional resources ranges from 40-100 GtC for oil fields and 90-400 GtC for gas fields. Deep aquifers are more widely available than oil or gas fields. If aquifer storage is limited to closed aquifers with structural traps, the potential global sequestering capacity is relatively limited—about 50 GtC, equivalent to less than 10 years of global CO_2 production from burning fossil fuel at the current rate. However, *if* structural traps are not required for effective storage, potential aquifer storage capacity might be huge; estimates range from 2,700 GtC to 13,000 GtC. (For comparison, estimated remaining recoverable conventional fossil fuel resources contain about 5,600 GtC.). Further research and demonstration are needed to assess the viability, safety and public acceptability of different storage options.

Another route to sequestration is enhanced recovery of methane from coal beds. CO_2 is already commonly in use for enhanced oil recovery.

The production of hydrogen from fossil fuels with sequestration of the CO_2 is likely to be a more cost effective way of producing hydrogen (without CO_2 emissions) than electrolysis using zero carbon electricity, though the latter is generally seen as the best approach in the long term. For this reason the former is often seen as a stepping stone to the achievement of a hydrogen economy in the long-term (see below).

3.4 New energy systems and facilitating technologies

Aside from the developments in particular technologies discussed above, the development of low carbon energy systems will also require changes in the infrastructure for energy supplies and the development of 'facilitating technologies'. In particular we will need to see:

- the development of energy storage technologies that substitute for the energy currently stored in fossil fuels;
- changes in the ways electricity transmission and distribution systems are managed, entailing more widespread use of decentralized sources that can also provide heat (small scale CHP); and
- low carbon 'energy vectors' for transport and storage of energy, of which the most promising is hydrogen.

Advanced energy storage systems: The list of alternatives under development is long: advanced batteries, electro-chemical storage (in electrolytes) for use in (regenerable) fuel cells, super-capacitors, superconducting magnetic storage, high speed flywheels based on carbon fibres, high pressure compressed air storage, and thermochemical storage. These are intended for short-term storage, generally on a small scale.

Hydrogen production and storage: Hydrogen is likely to be fundamental for a low carbon future whichever primary energy source is used. It is not a source of primary energy; it is a carbon-free energy carrier that has many potential applications, including vehicle fuel and centralised or distributed electricity generation.

There are five reasons for the interest in hydrogen: it burns cleanly, with no emissions of local air pollutants; it offers the prospect of zero CO_2 emissions when produced from a non-carbon energy source; its use would be associated with significant gains in efficiency when used in fuel cells and for combustion in turbines; it is a storage medium; and because it can be produced from a diversity of resources it is seen as a means of improving energy security.

There are several promising methods for its production: electrolysis of water using low carbon electricity; steam reforming of fossil fuels; direct production from sunlight (photo-electrolysis); and in situ formation from fossil fuel deposits. When it is produced via electrolysis of water using nuclear or renewable electricity, CO_2 emissions are zero. It can also be produced directly from fossil fuels with zero carbon emissions when the carbon is sequestered.

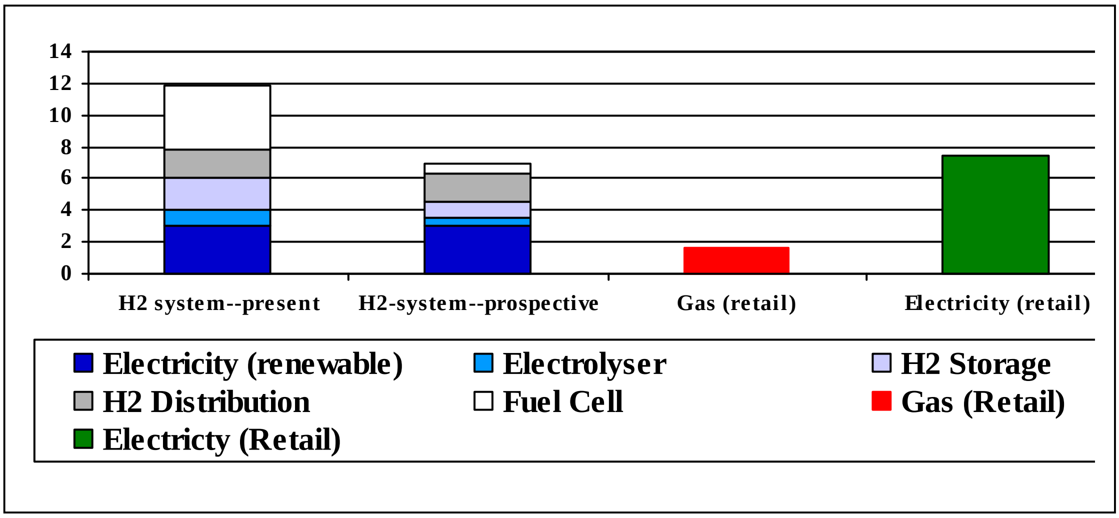
It is possible to store hydrogen on a large or a small scale, or for short term or for long-term—e.g. monthly, seasonal or annual purposes. For large scale long-term purposes geological storage in salt caverns (a practice used by the chemical industry) or possibly depleted gas fields and deep saline aquifers are seen to be the most promising options. Presently, storage as a pressurised gas is favoured.

Short term storage is possible in several forms: liquid (the boiling point is very low, however, about minus 250^{o} C), as a gas in pressure cylinders or storage tanks, through adsorption in metallic compounds, or through the chemical formation of synthetic hydrogen compounds.

The production and use of hydrogen would require innovations in the ways electricity, gas and transport fuel infrastructures are developed and managed. Transport fuelling infrastructures would change completely. There is also the possibility of using the electricity grid for 'harvesting' energy from a variety of large and small scale resources. This will, in turn, require the gas grids and distribution networks to be reconfigured and designed to become compatible with the production, storage and distribution of hydrogen. Figure 8.3 in Part II attempts to capture the sorts of changes involved.

The estimates shown in Figure 3.2 suggest that the costs would not be excessive. The costs of gas (in the form of hydrogen) would be higher than those of natural gas, as one might expect. Against this, the emergence of decentralised generation coupled with hydrogen offers the prospect of lower electricity costs in the long-term.

Figure 3.2: Unit Costs of Hydrogen System at the Retail Level: Current and Prospective (p/kWh), Compared with Current Retail Prices of Electricity and Gas in the UK.



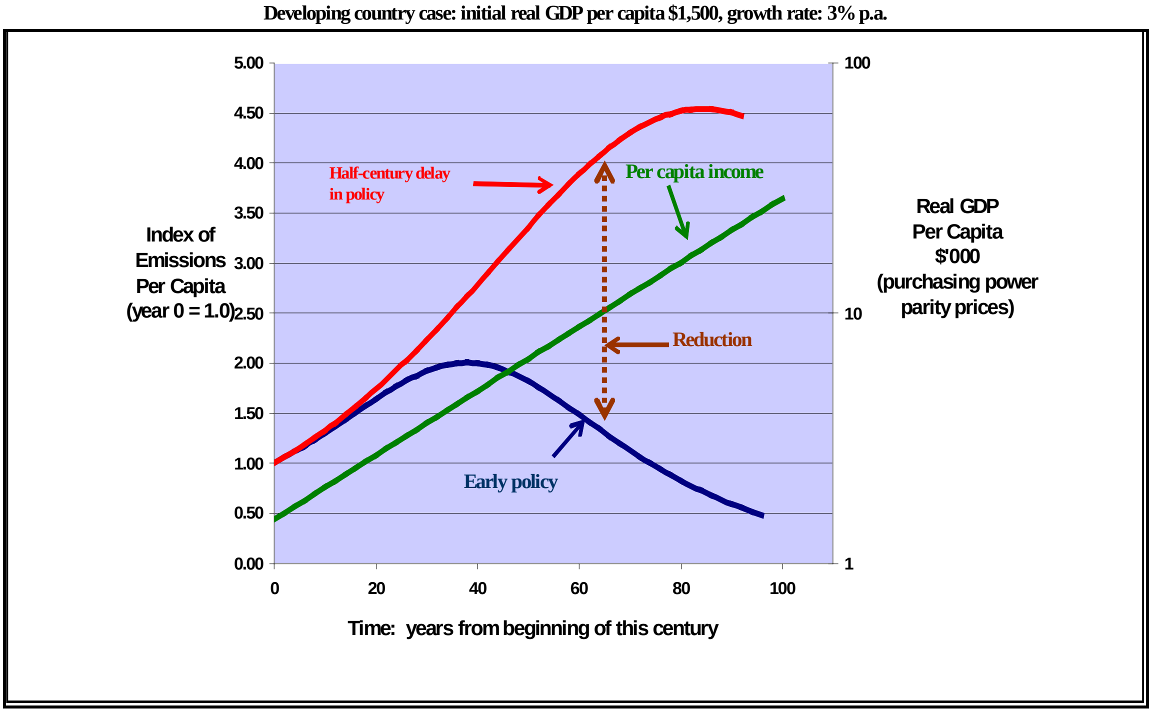
Source: Anderson and Leach (ICCEPT working paper). Note that the cost of hydrogen gas at the point of consumption is indicated by the point where the white bar begins in the two left hand bars, and of electricity where the white bar ends. See table 9.1 in Part II for the basis of the estimates.

The mix of technologies and practices that will be used will depend on relative rates of innovation, costs and the policy incentives provided by governments around the world. The mix cannot therefore be forecast with any precision. Furthermore some technologies are better suited for some countries than others. Solar is economically more attractive in tropical and sub-tropical latitudes than in western Europe, for example, and offshore resources more attractive in western Europe than in some other parts of the world. Afforestation projects to supply biomass energy are attractive where land is fertile and abundant, and also, as in many parts of Africa and Asia, where there is a need to restore degraded lands and watersheds. However, *whichever* mix does eventually emerge, it will have a profound effect on carbon emissions, since all the technologies discussed are low carbon.

3.5 Effects on CO_2 Emissions: the regional dimension

The effects of introducing low carbon technologies will differ between developing and the high income countries. In developing countries there will be an economic need to expand energy supplies several-fold to support economic growth, as discussed earlier, even allowing for gains in energy efficiency. This will inevitably mean a rise in their carbon emissions for some time, perhaps over the next 30-40 years. However, the introduction of the low-carbon technologies discussed would, at first gradually, and later rapidly, lead to major cuts in emissions. Figure 3.3 shows the potential for reducing emissions reductions through policy measures to promote innovation and the use of low carbon technologies. It is possible for developing regions to aspire to reducing emissions by 50% or so relative to what historical trends might suggest by middle of this century, and to 100% reductions in the second half.

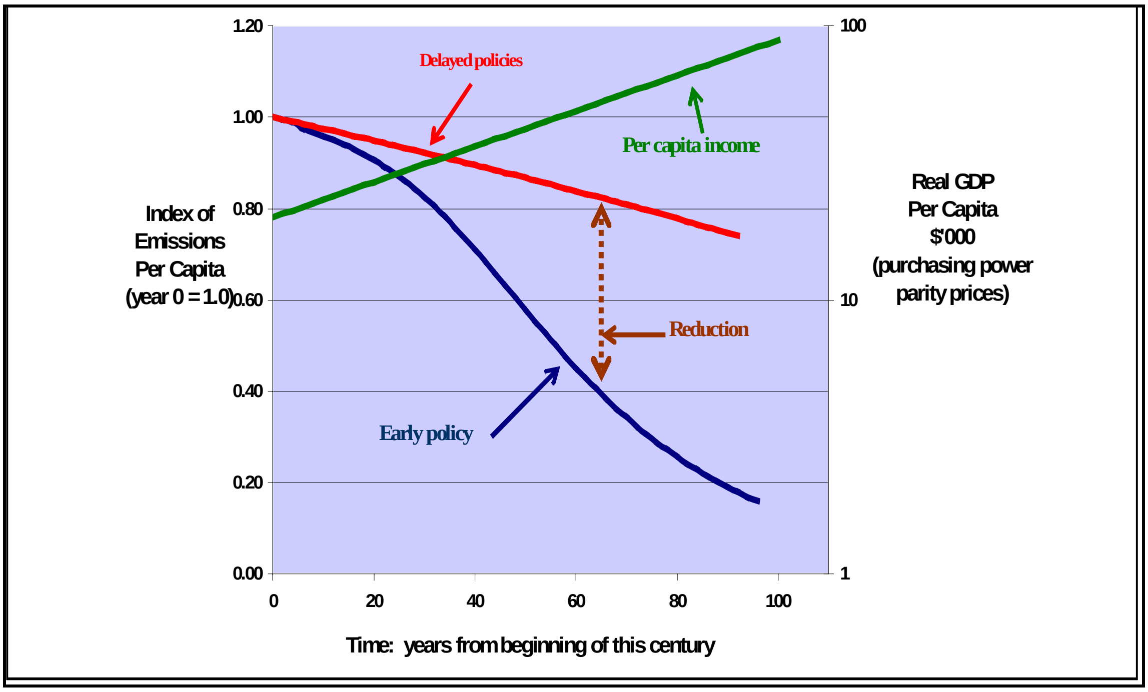
Figure 3.3: Effects of use of low carbon technologies on CO2 emissions. Developing country case: Initial real GDP per capita $1500, growth rate 3% PA.



Source: simulation studies undertaken at ICCEPT, using the model of Anderson and Cavendish (2001); also reported in the World Energy Assessment (2000). Model is available on the ICCEPT website.

In the high income countries, in contrast, whose energy markets are maturing, per capita income elasticities of demand are already low, the rising use of natural gas, and increasing energy efficiency, and the gradual introduction of renewable energy technologies are already leading to some reductions in carbon emissions. But, as with developing countries, a policy environment to favour the introduction of the non-carbon technologies discussed would likewise lead to major reductions in emissions; reductions of 60% by 2050 and 100% in the second half of the century have been shown to be feasible, and are supported by the estimates shown in Figure 3.4.

Figure 3.4: Effects of use of low carbon technologies (induced by policy) on CO2 emissions. High income country case: Initial real GDP per capita $20,000, growth rate 1.5% pa



Source: simulation studies undertaken at ICCEPT, using the model of Anderson and Cavendish (2001); also reported in the World Energy Assessment (2000). Model is available on the ICCEPT website.

It is not possible to give a precise breakdown of the contribution of the various technologies and practices reported here to the reductions of emissions. What we can say is that, on the basis of what we know now:

- A greater use of gas and energy efficient technologies will be the dominant source of emissions reductions relative to trend levels in the medium term.

- Renewable energy, along with hydrogen, will probably dominate in the longer term.

- Developing countries could make large cuts *relative to trend levels* through the use of such technologies, and will be ideal areas especially for solar and biomass, the latter initially for land restoration. As with the industrialised countries, however, a wide range of low carbon technologies will appeal.

- Industrialised countries could aspire to major absolute reductions of 60% by 2050.

Figure 3.5, which is intended to be indicative, provides some speculations on how energy systems might look. The arrow indicating 10%, 25% and 60% reductions refers to absolute reductions for the OECD countries and reductions relative to trend levels for the developing countries.

Figure 3.5: Examples of Possibly Dominant Technologies, now to 2050

	Now	2020	2050
Primary sources	Coal Oil Gas Nuclear Gas Hydro Biomass (combustion) Biomass (traditional)	Gas Oil High efficiency coal Wind (offshore) Solar (tropics) Biomass (gas'n) Biofuels (ethanol, DME) Geothermal Biomass (land restoration) CO_2 sequestration	Solar Offshore wind Solar thermal Solar PV (all regions) Wave Tidal New nuclear Biomass (various CO_2 sequestration Fusion?
Transmission, storage and transport of energy	Electricity (central) Gas pipelines Oil tankers Little elec. storage	H_2 (local production) H_2 (short term storage) New storage options Electricity (decentralised) Superconductors	H_2 (pipelines) H_2 (long term storage) Superconductors New storage options
Efficiency devices	Large/medium CHP Improved appliances Heat pumps Low energy buildings	Hybrid car - Biofuels Hybrid car – Oil Micro-CHP Fuel cells (stationary) H2 Fuel cells (vehicles) Advanced metering and controls Improved appliances Very low energy buildings	H2 Fuel cells (vehicles) 'Smart' appliances 'Zero energy' buildings
	10% reduction in CO_2	25%	60%

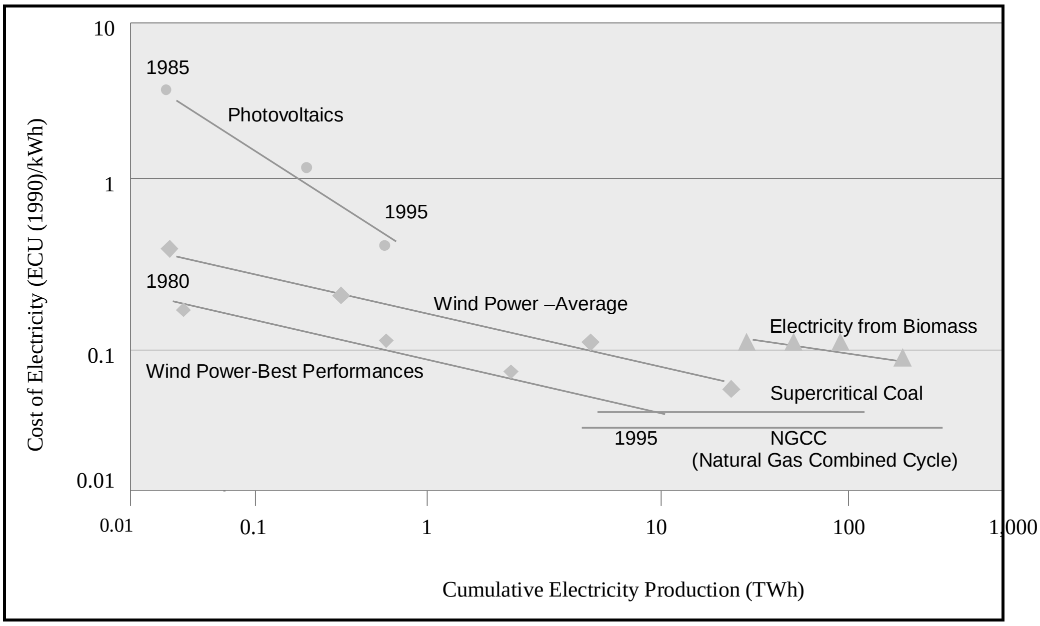
4. Delivering technology options: drivers and enablers

4.1 The Process of Innovation

The emergence of new technologies is usually the product of significant investment and in most cases emerging options are initially more expensive than the ones in widespread use. Progress often begins in small niche markets where higher costs are acceptable – for instance solar photovoltaics were initially introduced for applications in aerospace and remote telecommunications. There is then a process of learning-by-doing, of scale economies in the manufacture of the new technologies, and of further research, discovery and innovation as investment expands, all of which act to reduce costs and improve efficiency.

As a result, most technologies progress along a ‘learning curve’ where costs fall as markets expand, and this is as true for most low carbon options as it has been in other industries – as the example in Figure 4.1 illustrates. The rate of decline in costs is generally the greatest when the technology is in its infancy. Another effect concerns substitution: when the prices of the new technology are much higher than those of the ones it is competing with, there is often little scope for substitution, and it is only when prices converge that the rate of substitution begins to rise.

Figure 4.1: Learning Curve Data for Selected Energy Technologies



Source: IEA (2000)[6]

[6] Compressed scale makes supercritical coal and NGCC appear flat, in fact continued cost reduction in these technologies is widely predicted, albeit at a more modest rate than for less mature options - due both to lower learning rate and, because cumulative production is so much larger already, a much longer timeframe for each doubling of cumulative electricity production.

What sets apart the emergence of technologies and practices address environmental problems is that their development is unusually dependent on public policy signals—in particular signals to reflect the costs of pollution and the benefits of environmental innovation.

In addition there is the problem of establishing the market—the so-called commercialisation phase that follows on from RD&D. Energy technologies are long-lived and involve large and complex infrastructures—power grids, gas pipelines, oilfields, refineries and filling stations—and a raft of associated end use technologies and appliances. Alongside these infrastructures are institutions and markets to support the existing industry and a dedicated base of skills and professional disciplines in the labour force. As a result, existing technologies may 'lock out' newer alternatives for a long time, even those that offer environmental and economic improvement.

The dilemma for both policy makers and industry is thus that reducing costs to levels that compare favourably with those of the alternatives already in use may take years or decades. The upshot is that:

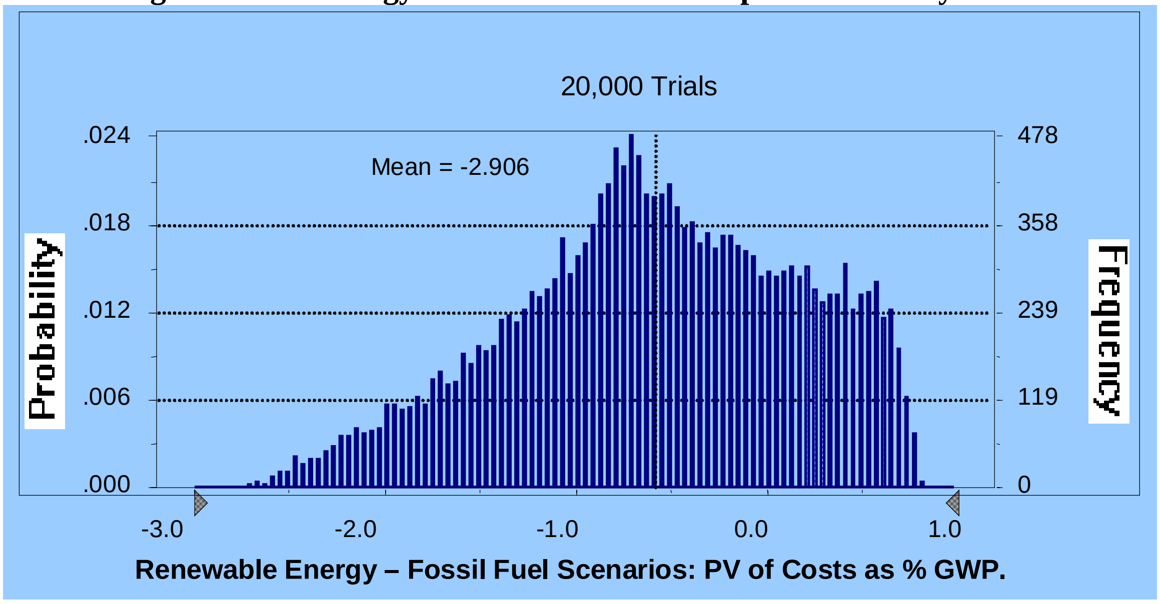
If the new technologies are to succeed there has to be a long-term financial commitment by both the public and the private sectors to their development. The object should be to stimulate innovation, nurture the new technologies and develop a supporting institutional and technological infrastructure, so as to deliver commercially viable and low cost low carbon solutions.

This need not be a permanently 'uphill' struggle. The large majority of environmental problems that have been solved required just such a commitment until the technologies and practices began to take root and become part of everyday practice—the elimination of smogs, acid rain and harmful emissions from vehicles are well documented examples as are the provision of safe water and waste water treatment. We see no reason why climate change should be an exception given the declining cost characteristics and the scope for innovation in climate friendly technologies.

4.2 Effects on Economic Growth and Development

The precise effects will depend on costs, which are uncertain. However, over the plausible ranges the estimated effects on growth vary from being positive—an economic surprise—to being negative but small. Figure 4.2 shows a typical probability distribution of outcomes, based on the present value of the costs of a transition to low carbon energy use as a percentage of Gross World Product (GWP).

Figure 4.2: A probability distribution of the projected costs of gradually substituting renewable energy for fossil fuels over the present century.



Source: Anderson and Papathanasiou (2000). GWP refers to gross world product. The figure is derived from simulating of alternative futures under a wide range of assumptions ('20000 trials' of cost and other parameters.

In line with many other studies going back to the early 1990s, the general consensus is that gross world product would be diminished by roughly one half of a year's growth over the next 50-100 years. In other words, the extent of the rise in income of people living in 2050 would be delayed by 6 months or so as a result of policies to address climate change. Yet this income, with good economic management over the coming generations should be several times higher than that of people living today.

Furthermore, this understates the case. The above calculations ignore other benefits arising from the low carbon technologies discussed such as a better local environment, and ignore the benefits of mitigating climate change itself. Taking these into account as best we can, estimates point consistently to developing and industrialised countries alike being economically better off not worse off with the policies and innovations discussed in this report.

4.3 The role of policies: (a) the national level

Many countries are beginning to accept this conclusion. All OECD countries support the development of renewable energy and efficient end-use technologies. This process began in the 1980s and early 1990s, and is presently being revisited in the light of experience and new evidence.

There is an active exchange of ideas and experience through conferences, scientific and engineering publications and through the aegis of international organisations such as the IEA, the Global Environment Facility and the World Bank. In addition, a large number of developing countries have policies explicitly to support renewable energy and energy efficiency, including all countries in South and Central Americas, all South and East Asian countries, and most countries in Central Asia and Africa.

There is a good basis of experience to build on. A review of national policies is outside the scope of this paper. But one implication for climate change policies clearly emerges from this review of technologies. Policies to address climate change need three elements not one:

a) Direct instruments and targets focussed directly on carbon emissions—to internalise the externality and reward successful low carbon investments.

b) Direct support for innovation, such as R&D; demonstration projects; public procurement policies to support innovative technologies; obligations or commitments to develop renewable energy; tax incentives or credits for innovative projects; funding and other financing mechanisms (such as the Carbon Trust in the UK) to seed fund new initiatives and share risks; and of course education and skills training programmes in the new technologies and practices.

c) Demand-side or 'commercialisation' policies such as market stimulation through tax incentives, tradable obligations certificates (similar to the renewables obligations certificates recently introduced the UK), and other such incentives to encourage use and learning by doing—more technically, to internalise the positive externalities of innovation.

At the international level (a) has occupied the lion's share of the attention while at the national level governments are increasingly focussing on (b) and (c), not least the US which retains very strong technology policies, and is a leader with respect to most of the technologies discussed in this report. Ideally we need a combination of all three at the national and international levels.

Without innovation the costs of addressing climate change will be immense—and so will be the taxes required to induce the required developments. With innovation, in contrast, the costs will be much reduced. Hence a focus on innovation through (b) and (c) would have the merit of reducing the burden of environmental policies on taxes associated with (a), and for this reason would greatly facilitate the introduction of climate change policies.

4.4 The role of policies: (b) the international level.

Policies at the international level so far have had two aspects:

a) Attempts—only partially successful—to agree target reductions in emissions by the high income countries, and accompanying mechanisms allowing the nations to trade off these commitments to reduce costs, for example through the Clean Development Mechanism.

b) The establishment of the (very successful) Global Environment Facility (GEF) to finance *proven* low carbon technologies and practices in developing regions, primarily proven renewable energy and energy efficiency projects.

Our analysis suggests the need for two more elements in international policies:

c) Agreements among countries, both developing and industrialised, which would formalise their commitment to innovation. We suggest (echoing the recent

Brazilian Energy Initiative, under the leadership of Professor Jose Goldemberg) that this should become a formal part of the agenda on climate change negotiations.

d) The establishment of a funding and institutional arrangement, incorporating public and private interests, to support the development and use of advanced non-carbon energy technologies in developing regions, to complement the GEF which already supports proven technologies.[7] The idea would be to move the 'technology frontier' forward. Such arrangements exist for nuclear power (both fission and fusion), but not for innovations in renewable energy and efficient end-use technologies.

The experience of the Global Environment Facility is that funding mechanisms such as (d) can enjoy substantial leverage. As of June 30 2002 the GEF had a portfolio of renewable energy and efficient end-use projects aggregating to over $8 billion in 70 countries; for every dollar of grant finance provided by the GEF, more than five dollars of additional resources had been levered from private and public resources, excluding the additional and very substantial resources levered through local policies.

All the technologies discussed in this report are tradable goods, and their diffusion across countries will be greatly facilitated by trade. We have taken it as self-evident that international trading arrangements will need to support both national and international policies that encourage the development and use of low carbon technologies on the lines discussed in this and the previous subsection.

[7] A similar proposal was put forward by in the report of the US President's Committee of Advisers on Science and Technology (1999) *Powerful Partnerships: The Federal Role in International Cooperation on Energy Innovation*.

5. Conclusions: The Opportunities Ahead

There are five conclusions:

1. ***Cutting CO_2 Emissions***. Substantial cuts in emissions from energy production and use could be achieved over the coming decades. The situation varies between the industrialised and the developing countries. The industrialised countries are better placed to cut emissions in absolute terms since their energy markets are maturing; substituting low carbon fuels for carbon intensive ones, and improvements in efficiency, are less likely to be offset by demand growth. Indeed the process of substitution is already beginning. In several countries it is being promoted by incentives to cut emissions directly, in others by a focus on innovation, and in some by a combination of both approaches. Several studies have shown (including the present one) that 60% cuts by 2050 are technically and economically feasible, and 100% cuts beyond then. (Section 4.)

In developing countries, where per capita consumption of energy is still very low, further and substantial growth of energy use using fossil fuels is inevitable and is needed to support their economic development. However, there are opportunities to reduce the *growth* of emissions by more widespread use of renewable energy and energy efficient technologies and processes. Eventually, as these technologies take root, substantial reductions and the achievement of a zero carbon energy system will be possible. (Section 4.)

Given that the world's consumption of fossil fuels—already equivalent to 8 billion tonnes of oil per year—will rise for two or three decades before it declines, it is evident that the use of gas (an abundant and relatively clean fuel) and the more efficient and cleaner methods of utilising coal and oil will be important. This too will reduce the rate of growth of CO_2 emissions, and have substantial local environmental and economic benefits.

2. ***Technological Options***. There are three promising options in particular whose aggregate contributions together could amply meet, over time, the world's growing energy needs. (Section 3.) They are:

a) *Renewable energy technologies*—solar, onshore and offshore wind, offshore tidal stream and wave energy devices, geothermal energy, and biomass from wastes and crops. The relative merits vary greatly between countries, primarily because of variations in natural resource endowments. But it is generally true that the renewable energy resource is abundant in all regions of the world, potentially available in perpetuity, and that the conversion efficiencies for harnessing it have improved appreciably and continue to do so. And all the technologies are associated with zero emissions of the principal greenhouse gases.

b) *Efficiency in energy production and use*. Even though energy efficiency generally improved tenfold or more over the past century, research shows the scope for further innovations and improvements to be far from exhausted. The hybrid (gasoline/diesel-electric) and fuel cell vehicles now under development and decentralised forms of combined heat and power are just two of a long list of possibilities.

c) *Changing the nature of the energy system: hydrogen, storage and decentralised forms of combined heat and power*. Hydrogen holds the key to opening up the transport markets to all non-carbon energy resources in the long term, including the use of fossil fuels with carbon sequestration. It also offers prospects of major gains in energy efficiency through the use of the fuel cell and micro turbines for decentralised heat and power. Lastly, it is one of several routes, which include innovations in small scale storage technologies, for solving the intermittency problem of some renewable energy options. All such changes will entail major changes in energy infrastructures and systems, and in the ways they are operated and regulated.

Two further options which will compete with the above are:

d) *Decarbonisation of fossil fuels with sequestration of the CO_2*. This is a promising option being actively researched by industry. It is also a low cost route to hydrogen production. While environmental concern may limit the extent to which this option can be pursued, it has a useful role to play especially in regions with substantial coal reserves.

e) *Nuclear power*. Nuclear fission is a familiar and well tested option—which raises the equally familiar and still unresolved issue of public acceptance, especially regarding the issues of nuclear wastes, decommissioning and proliferation, all of which will restrain—as they have in the past—the uptake of new generations of reactors. New smaller reactors, with improved characteristics along several dimensions are however now being pursued, and are promising in the medium term. Whatever its future, nuclear fission cannot be depended upon to deliver a low carbon future by itself, or even make more than a modest contribution.

   Nuclear fusion is still being pursued, as it has been for 50 years, and is still unproven; according to the most optimistic estimates it will not be commercially available for another quarter of a century (more often the estimate is half a century). Some novel concepts such as inertial confinement are reported to show promise.

In our judgement (a), (b) and (c) are the best prospects for meeting world energy needs in the long term while mitigating climate change; the first two were also emphasised by the G8 Task Force on Renewable Energy in July 2001. The actual mix of technologies deployed within these categories varies between countries. We have argued for a broad portfolio of investments in these three areas.

It would, in our judgement, be a mistake to seek a 'magic bullet' in just one or two technologies, given the diversity of situations across countries and the diverse and often complementary merits of the alternatives.

3. *Costs and the need for a policy commitment.* With important exceptions, the private or 'market' costs of the above technologies are higher than those of fossil fuels—sometimes appreciably higher. (Section 3, Table 3.2.) Exceptions are in the area of energy efficiency, and some markets for renewables such as geothermal energy in favourable locations and "off-grid" solar energy in rural areas. But as a general rule costs are higher, and the technologies will not move forward without supporting policies to bring about a convergence of public and private interest in market decisions. Over the longer term, there are grounds for believing that costs will converge as a result of innovation, and in some cases may fall below the costs of fossil fuels.

But over the next 20 years or so significant investments will be required, and they will be loss making unless industry receives the required regulatory and financial incentives to take on the task. We have suggested that we need three elements in policy. First, a direct incentive to reduce emissions, to 'reward the successful low carbon entrepreneurs'. Second, strong RD&D programmes (especially in the areas (a), (b) and (c) above). Third, market stimulation policies to encourage further innovation ('learning by doing') and use. It is encouraging that many countries are moving in these directions, albeit often slowly.

4. *Living Standards and Development.* Neither the living standards of the rich countries, nor the aspirations of the developing countries for economic growth and development, need be sacrificed in a long-term transition to a zero carbon world energy system. In fact, when the benefits of innovation and the environmental benefits of the technologies and practices just emphasised are taken into account, both developing and the rich countries would very probably find themselves better off. (Section 4.)

5. *A new international initiative?* The above conclusions show that we have a unique opportunity to address the problem posed by global warming by supporting innovation at the international as well as national levels. National governments around the world, including all countries in the OECD, and a large number of developing countries, are inching their way toward such policies, which we suggest *should form part of international agreements on ways of addressing climate change*. This alone would be a step forward, as innovation is currently only on the fringes of the international agenda, including the Kyoto Protocol.

Aside from introducing innovation into the international dialogue on ways of addressing climate change, we have suggested two further steps:

a) The establishment of an international funding mechanism and institutional arrangement to foster the development of advanced renewable energy and energy efficient technologies, including hydrogen production and use. To complement this on the policy front:

b) Exchange of experience between industrialised and developing countries on ways of stimulating such innovation.

Such arrangements exist for nuclear power and fossil fuels, with the partial exception of carbon sequestration. We also have the (very successful) institution of the Global Environment Facility (GEF); however, its remit requires it to concentrate *only* on proven renewable energy and energy efficient technologies, *not* on innovation. We have no international institutional or financing arrangement in place to foster innovative renewable energy technologies, hydrogen and new, more efficient energy systems. Yet there is much that could be promoted by such an arrangement.

The *modus operandi* and institutional arrangements for an *international initiative to develop renewable energy and the hydrogen economy* (as it might be termed) would need to be worked out. It would require a joint effort between the public and private sectors. The experience of the GEF shows that if appropriately coupled with multilateral finance it would also enjoy considerable financial leverage, and act as a catalyst for the formulation of policies in support of 'climate friendly' innovations worldwide.

The innovations of recent years, supported by the national policies of many countries and the work of the international institutions, have together provided solid operational experience. Policies are continually being reassessed based on the lessons learned so far, and indeed there has been much experimentation and innovation in policy making, especially in the area of market based incentives. Historical experience shows that policies have a profound effect on technology development and the way energy systems evolve. They will continue to have a profound effect in the future.

Part II

Technologies and Practices: An Assessment of Options

Part II

Technologies and Practices: An Assessment of Options

This part of the report provides an overview of the leading technologies and practices that could help meet rising global demands for energy services whilst reducing emissions of CO_2. As discussed in Part I, it is possible for innovations to reduce carbon emissions at every stage of the 'energy chain': through exploiting low carbon energy sources; through efficiency gains in primary conversion, energy transmission and end use technologies; and through changes in the very nature of energy systems.

The following sections therefore consider options with the potential to reduce emissions at each point in the chain. A large number of options exist or are emerging and there is much scope for continued innovation, 'learning by doing' and scale economies to improve technologies and lower costs. But technologies differ greatly in terms of their technical characteristics, costs and technological maturity, future prospects, and the scale of the global potential.

In addition, low carbon options have diverse characteristics. Some, such as intermittent renewables, introduce new challenges. Others can facilitate the introduction of a wide range of new technologies or precipitate changes in the way energy is transported and used; energy storage and hydrogen are examples. Some technologies are better suited to specific geographical regions and many technologies have non-carbon environmental impacts and implications for other policy priorities, such as security of supply.

The analysis is structured as follows:

a. An overview of resources, technology characteristics, maturity and costs, progress to date, and future prospects for technologies in the following categories;

- Low carbon primary energy sources
- Technologies for improving efficiency in energy conversion and use
- New energy systems and facilitating technologies

b. Assessment of regional issues, implications for non-carbon environmental impacts and other policy goals, timescales for development

6. Low carbon sources of primary energy

Primary energy is available from three sources; fossil fuels, renewable energy, and nuclear power. Renewables and nuclear power are both low carbon sources, whereas fossil fuels can be made 'low carbon' through the separation and storage of CO_2 such that it is prevented entering the atmosphere. This section considers all three.

6.1 Renewable Energy

Renewable energy encompasses a wide variety of resources and technologies. Renewables currently supply 10 – 15% of world energy, but most of this is from the use of dung and foraged firewood in rural parts of developing countries (~10%) and large hydro-electric schemes (3%). The former is a source of ill-health for rural people and environmental degradation (see below); the latter has limited scope for further expansion, is land intensive and can also create environmental difficulties.

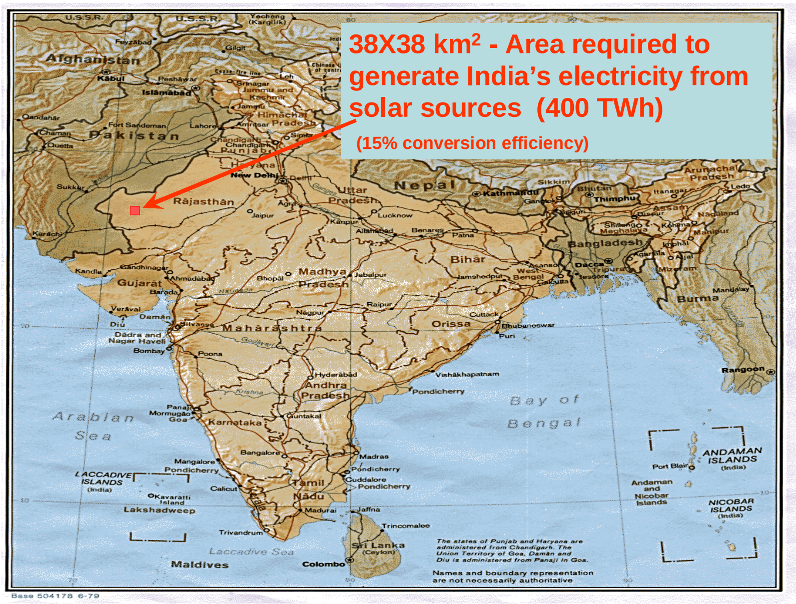
The following concentrates on solar technologies, wind power, geothermal, wave and tidal technologies, and various options for sustainable usage of biomass (plant based materials and plant and animal wastes). Each of these has the potential to supply large amounts of energy and scope for considerable technical improvements and cost reduction – though technical maturity differs considerably. However all are currently little used compared to both the scale of their potential and the size of the global energy market. Taken together they account for just 1% of world primary energy consumption.

Solar Energy

Resource

Solar energy is abundant. About 30% of its spectrum is theoretically available for electricity generation and the rest can provide heat. The amount of land that would be required in theory to meet the whole of the world's primary energy requirements today from solar energy is less than *one percent* of the area currently under crops and agriculture; in practice, such land would not be required as buildings and uncultivated areas can be used (see below). The hypothetical calculation in Figure 6.1 for India provides an indication of the yield of the resource.

Figure 6.1: The Abundance of the Solar Resource



Solar energy is not uniformly distributed: the available resource in the tropics is around 3 times that in temperate and cloudy latitudes; moreover, the coincidence between solar outputs and energy needs is much better in sunny latitudes where there is a strong demand for electricity for daytime air conditioning. Despite this, the absolute resource is large even in cloudy climates – studies for the UK government (DTI 1998) suggest that photovoltaics on buildings could in principle supply around two-thirds of UK annual electricity demand.

Technology options
There are basically three technologies for turning solar energy to commercial energy:

- Photovoltaics (PV) – which directly convert light into electrical current
- Solar-thermal systems
- So-called 'passive solar' technologies where building design maximizes solar lighting and heating. These are discussed under energy efficiency.

PV technologies

Technology characteristics, maturity and costs
PVs consist of a semi-conducting material, currently silicon is most common, which converts photons of light into electrical current by means of the photoelectric effect. Typically available in the form of panels or modules they can be used for four main types of application:

- small scale provision of electricity for electricity supply in remote regions that do not have a well-developed electricity grid

- very small scale applications such as calculators

- Building integrated systems (BIPV) that may also be connected to the grid; specialized products are emerging, such as solar roof tiles

- Central station supplies, where large arrays of solar modules provide electricity for the grid

Applications include remote telecommunication stations, water pumping, battery charging and solar home systems in remote parts of developing countries, supplying daytime air-conditioning demands in hot climates, and architecturally attractive applications on roofs and facades of buildings. Grid connected applications (mostly BIPV) now account for over 50% of the world market, stimulated largely by supportive policies in Japan, Germany, the US and other industrial countries.

PV systems currently cost around $5,000 per kW, plus installation costs. They are still several times the costs of other renewable energy technologies such as wind. However, they often can be the lowest cost means to provide small amounts of electricity in remote off-grid applications. BIPV applications are usually considered in terms of their competitiveness with retail electricity prices, and in a limited number of cases PV materials are able to offset the costs of alternative building materials and this can improve the economics considerably (if high cost cladding materials are replaced with PV). However, BIPV is largely dependent upon policies, such as *net metering*, by which consumers using PVs can sell surplus electricity back to the grid.

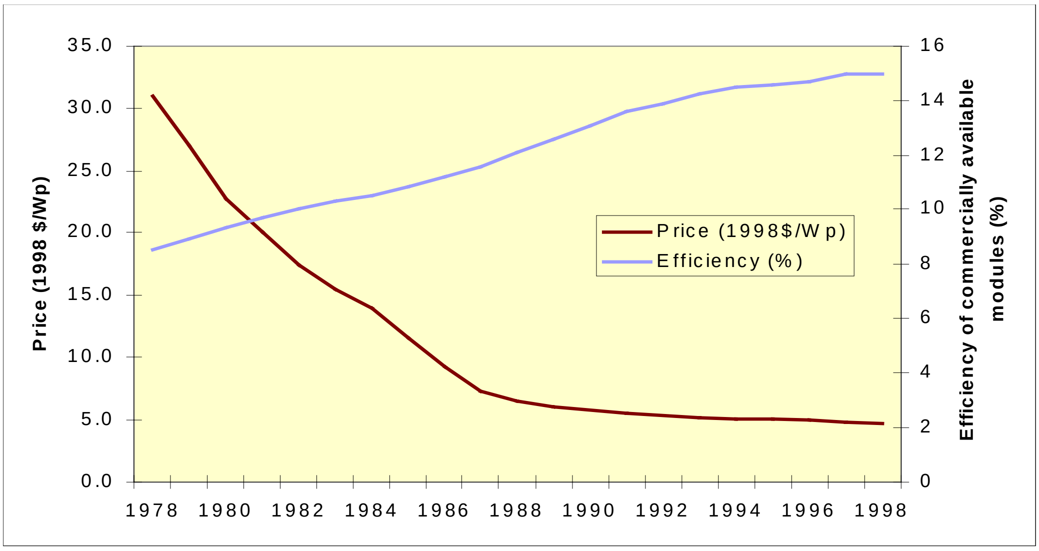
Progress and future prospects

The initial impetus for the development of PV was to power satellites in the 1960s and 1970s, when costs were as high as $300,000 per kW, and markets aggregated to less than 1 MW per year. PV still performs this role. But as developments proceeded, costs declined rapidly and terrestrial applications emerged. World markets are still small in relation to those commonly found in the energy industry: shipments amounted to 250 MW in 2001 (as compared to over 70,000 MW of new electricity generating plant); but they are expanding at over 25% per year.

The potential for further cost reductions as markets expand is appreciable. The technologies are small scale and modular, and the scale economies of batch production and new manufacturing techniques have been barely exploited. Each doubling of the cumulative volume of production, supported by RD&D programmes, has seen costs decline by around 20%. In addition, conversion efficiencies of PV modules have seen continuous improvement through the use of new materials and cell designs (Figure 6.2). Most commercial PV designs are currently based upon modules assembled from individual crystalline silicon cells. These entail several complicated stages of manufacture. One of the issues for the future of PV is how fast crystalline silicon can be replaced by so-called ‘thin film’ designs in power generation applications, which are inherently simpler and hence cheaper to make. In the long term a ‘third generation’ of PV materials, currently at the laboratory stage, may be able to deliver even more radical reductions in cost – semi-conducting polymers (plastics) are one example.

Many independent studies suggest that the costs of PV will continue to fall and assessments based upon a diversity of methodologies are in general agreement. They suggest that it is plausible to envisage module costs of $1000/kW or less by 2020 – this would allow BIPV to provide electricity below today's retail price in sunny area of the world (PIU 2001a, WEC/UNDP 2000, IEA 2000).

Figure 6.2 Price and conversion efficiencies for PV modules



Source: IT Power Ltd.

Solar water heaters (SWH)

Technology characteristics, maturity and costs

These rooftop panels for capturing radiant solar heat can be seen on millions of homes and commercial buildings in countries with sunny climates. The technology is generally considered 'mature'; market growth will yield economies of scale and ongoing efficiency improvements, but major technical breakthroughs are not expected. In regions where the use of the technology is well established, solar water heaters (usually augmented by an electrical immersion heater) are fully economic. However this is not the case in cooler climates, for several reasons: the solar resource is much poorer, and systems provide a smaller proportion of hot water needs; domestic space heating requirements necessitate the installation of a central heating boiler (as in the UK) or have given rise to the development of heat networks and municipal scale combined heat and power plants (as in many Scandinavian towns). These can deliver hot water at low incremental cost. Gas grids are much better developed; markets for SWH are much less developed, which increases purchase and installation costs. This does not mean that SWH has no benefit in such climates, but does make full commercial viability rather less likely.

Progress and prospects

SWH could be adopted far more widely in sunny climates, particularly in developing countries. It is notable that SWH have only really taken off in countries where policy encourages it (for example Greece), and may be held back in some developing countries by lack of skills and by policies that distort energy markets (through subsidies). The implication is that even well-proven and low cost technologies may require positive action on the part of policymakers.

Numerous other low temperature uses exist in industry and agriculture, such as solar drying. It is not possible to deal with these in this short document.

High Temperature Solar Thermal Technologies

Technology characteristics, maturity and costs

High temperature solar devices can be used for desalination, detoxification of waste materials and for electricity generation. But the main use so far is for electricity generation, in which mirrors are used to concentrate a large amount of solar energy onto a receiving element and enough heat is raised to make high temperature, high pressure steam. For electricity generation, solar concentrators can achieve conversion efficiencies of up to 40%. Most operational experience to date has been obtained from the parabolic trough schemes in California[8], whose aggregate capacity is 400 MW; they were installed in the 1980s, and have an exceptionally good operational track record over a 15 year period.

Progress and prospects

Progress has languished over the past decade because policies have not been supportive. Costs are quoted in the range $700-1500/kW, and there is potential for further progress. We would emphasise the following:

- The modularity of the technologies, which holds the promise of significant scale economies from batch production.
- Short construction times. Plant can be installed and running in less than a year.
- The abundance of the solar resource, especially in the dry tropics.
- Good conversion efficiencies (prospectively higher than for PV for clear skies).
- A diversity of promising approaches are being pursued.
- Further cost reductions through direct steam generation.
- They could become a good complement to hydro systems in developing regions, since there is an especially abundant resource in the dry season.
- The high temperature systems in particular also offer the prospects of solving the intermittency problem through thermal and thermo-chemical storage.

Aside from the projects in California there has also been operational experience in research centres in Spain and Israel. Given its promise in developing regions this is a technology well-suited for development through international co-operation; projects are planned in several countries with the support of the Global Environment Facility[9]. The technology is best located in desert regions, often remote from existing grid

[8] The sun's energy is focussed onto a central heat receiving element using parabolic mirrors. The heat is used to raise steam to fairly high temperatures of around 400^{o} C, though much higher temperatures are available in principle from systems which focus the energy onto central receivers.
[9] The financing arm of the UN Framework Convention on Climate Change.

infrastructure. While this of course adds to costs, the aggregate capacity of solar projects that could be developed in such regions is very large; the land intensity is only one hundredth of that of the average hydroelectric project for instance.

Wind: onshore and offshore

Resource

Estimates of wind resources depend on the availability of sites, turbine size and wind speeds. Nevertheless it is clear that wind resources are large on global scale and, in principle, exceed global electricity demand by a substantial margin.

Perhaps of more direct value are the detailed assessments of wind potential undertaken by many countries. Substantial resources have been identified around the world (Western Europe, the US, China and India are examples). UK government data suggest that offshore wind farms around Britain could provide around one third of annual electricity, for example, with cautious assumptions about available 'sea space'.

Technology characteristics, maturity and costs

Wind technologies fall into two distinct types: large turbines, designed to supply electricity to the grid, which are typically in the range 1-2 MW rated capacity and with blade diameter of around 100 metres and small turbines rated from around 3kW up to around 100kW, which are widely used in the leisure[10] and off-grid markets. In the interest of brevity we focus here on the large and grid-connected machines.

Wind markets have seen substantial growth (see table 6.1) and technologies have increased in size and declined in cost. As the technology has matured large wind machines have become increasingly standardised – all are now broadly similar three bladed designs. However the potential for innovation has not been exhausted (see below). Onshore wind is now able to deliver energy at average costs of around 4 cents/kWh[11]. This makes wind similar in cost to coal-fired generation in many countries, but still 50% more expensive than the lowest cost option; high efficiency gas fired plants.

Table 6.1: Cumulative Capacity of Wind Energy Installations (MW)

Region	1997	2001
North America	1,638	4,440
Latin America	42	103
Asia	1,108	2,162
Europe[12]	4,793	16,362
All other regions	57	125
Total	**7,639**	**23,270**

Source: UNDP/WEC (2000) and *Wind Power Monthly*.

[10] Battery charging on yachts for example
[11] Wind costs are very site specific, and highly sensitive to wind regimes. Costs quoted are typical for a moderate wind speed
[12] Figure for 2001 includes Russia and former Soviet republics. Note that more than ¾ of European wind power (around 13GW) is in just three countries – Germany, Denmark and Spain.

Progress and Prospects

Wind has seen rapid market growth and sustained cost reductions in the period from 1991. Total installed capacity worldwide increased more than ten-fold, with market growth averaging 22% per year in this period, accelerating to around 30% per year in the period from 1997. Since the first wind farms of the late 1980s:

- The annual energy output per turbine has increased 100-fold
- Turbine rated capacity (for typical commercial machines) increased from 55kW to 1 MW or more
- From 1995 - 2000 the weight of turbines per kW installed halved
- From 1997 - 2000 noise levels were halved

These factors have reduced the capital costs and improved the efficiency and reliability of the turbines. As the industry has matured, learning has reduced design, planning and installation costs and market growth has brought economies of scale.

There is scope for cost reductions through site optimisation and innovations in blade and generator design and in grid connection using power electronics. However, the pace of cost reductions will decline as the technology matures. Recent work for the UK Energy Review suggested costs for onshore wind are likely to fall to around 3.0 cents/kWh at good sites.

There is, in principle, very substantial potential onshore development in regions where land is abundant. Even if the rapid market growth rates seen in the previous ten years continue for a further 15 years, installed capacity would still be less than 10% of the global technical potential[13].

However, it appears likely that, with supportive policies, markets will continue to expand most rapidly in OECD countries in the near future, notably Europe and the US. There is some evidence that development in Europe is beginning to be affected by availability of suitable sites. As this is the region that has seen the highest growth in the last 10 years and has the most supportive policy environment for wind energy, continued development is also likely to depend upon the success of offshore wind.

The move offshore

At present little offshore wind capacity is installed anywhere in the world. As with onshore developments during the 1990s, Europe is the lead, with all the world's operating offshore capacity and ambitious plans for future development.

[13] Technical potential is more than 7000GW; 25% growth per year over 15 years would result in 570 GW.

Table 6.2: Offshore wind progress and plans in Europe

Country	Built	Planned/Proposed
UK	4 MW	Existing development at Blyth only 2 turbines close to shore, however the recently auctioned Crown Estates sites would, if successfully developed, lead to 1000 – 1500 MW by 2010
Denmark	212 MW	750 MW by 2008, long-term aim 4GW, first large development - 160 MW farm at Horns Rev, commissioned in 2002
Germany		Plans to secure 25% of electricity from offshore wind by 2030, sites equivalent to 10GW identified. Initial plans (sites with permits) 3GW. 500 MW expected to come on stream in 2003
Sweden	22 MW	175 MW under development, long-term potential ~ 3GW
Netherlands	19 MW	1500 MW by 2020, 240MW well advanced
Ireland		500 MW + (plans for farms at Dublin Bay and Arklow Banks)

The first large-scale offshore wind farm was completed in September 2002. Horns Rev, 12 km off the Danish coast, consists of 80 turbines and is rated at 160MW, with water depths of up to 20 metres. Several countries have plans for developments of a similar scale (See Table 6.2), a large resource has been identified, and offshore wind is expected to reach around 2 GW installed capacity by 2005 and grow at around 800 MW/yr thereafter.

Offshore wind currently delivers electricity at a cost of 6 to 9 cents/kWh – around twice the cost of onshore wind at good sites. Installing wind turbines offshore obviously incurs additional costs. However, engineering studies suggest that there is considerable potential for other factors to offset these costs. Wind regimes are generally higher and more stable offshore and the absence of noise constraints mean that turbines can spin faster – which increases output for a given size of machine, and reduces blade size and loadings on bearings and structures relative to onshore machines. Larger turbines, variable speed DC drives, and improved cabling and forecasting techniques are also predicted to reduce costs and there is the possibility of hybrid devices, such as those combiningwind/wave and wind/tidal stream technologies.

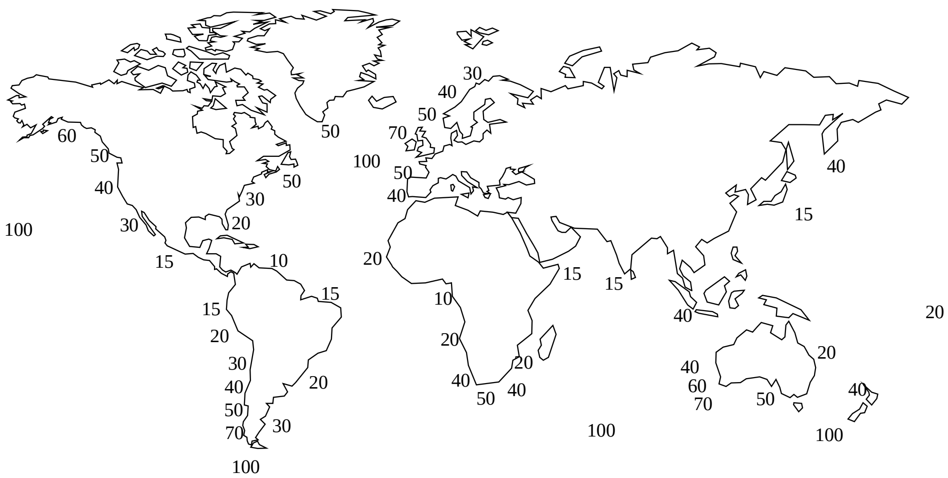
As a result, costs are widely predicted to fall; the UK Energy Review suggested that costs could fall to around 3 – 4 cents/kWh as development proceeds. Despite limited experience offshore, costs have already fallen: Horns Rev is expected to deliver energy at around 50% of the cost of early developments.

Wave and Tidal

Resource

The potential energy that could be practically extracted from tides and waves is large. For the UK alone it has been estimated that nearly 100 TWh per year (30 per cent of the country's electricity requirements) could be met from a selection of the most promising sites,[14] though other estimates are seven times this figure. However, there is still limited data on the global potential.

Figure 6.3: Global average wave power levels (Thorpe 1999)



Wave power levels are approximate and given as kW/ m of wave front

Technology characteristics, maturity and costs

Wave and tidal devices fall into three categories:

- The most developed ocean technologies are tidal barrages, where a large dam-type structure is used to control the flow of the tides through estuaries so that they can drive a largely conventional hydro-electric plant. Working examples include the 240 MW facility at La Rance in France, a 25 MW plant in Canada and a 100 MW plant in China.

- Wave power, for which there are numerous designs, harnesses the rise and fall of the waves to generate electricity.

- Tidal stream devices harness the movement of the tides to generate electricity without construction of a large dam-type structure; leading designs resemble under water wind turbines.

[14] House of Commons: Science and Technology Committee, Session 2000-2001, *Seventh Report: Wave and Tidal Energy*. London: The Stationery Office. HC 291

Tidal barrages have been largely ruled out on cost grounds – the Severn Barrage proposed for the UK would cost around £14 billion ($20 billion) to construct and energy costs would be in excess of 15 US cents/kWh – even allowing for very long-term amortisation of costs. Wave and tidal stream devices do not require the enormous civil engineering costs associated with tidal barrages. However they are currently at the R&D and prototype stage, with only around 1 MW of wave energy devices installed worldwide, all demonstration projects. There is currently no large-scale tidal stream capacity operating, though prototypes are being tested and several promising designs exist.[15]

Progress and prospects

Wave power has a long history. The first patent for a wave energy device was filed in 1799, and by 1973 there were 340 British patents for wave energy devices. The number continues to rise. R&D was initiated in several countries following the second oil price shock and numerous prototype devices have been developed. However, the initial enthusiasm gave way to some scepticism because of the high cost estimates associated with early prototypes. Despite this, progress continues to be made. Several companies are developing and deploying new devices that represent a significant improvement over older concepts. Wave and tidal are just beginning to emerge from the conceptual stage, and large scale demonstrations of research concepts are now entering the water for the first time.

Of those devices that have been deployed, for the most part near-shore and shoreline devices, costs are in the region of 7 – 9 cents/kWh. But overall, there is much uncertainty surrounding the economics of wave energy, reflecting the relatively immature status of the technology and market. Whilst it is not yet clear as to which of the numerous prototypes will succeed, the early stage of development does suggest that there is great potential for costs to fall. Technologies are modular, and development can proceed in such a way that projects are gradually scaled up.

Geothermal energy

Resource, technology characteristics, maturity and costs

Geothermal energy flows from the Earth's hot interior due to the movements of crustal plates. It is commonly tapped where zones of high heat flow are close to the surface. It is a proven resource, and has been used for electricity generation and for the production of heat for industry, space heating, aquaculture and other purposes for over 70 years. A World Bank report[16] notes that

> "In over 30 countries geothermal resources provide directly used heat capacity of 12,000 MW and electric power production capacity of over 8,000 MW... Geothermal plants offer several advantages: they are simple safe, and modular (1-50MWe), have short construction periods (approximately one year for a 50-MWe plant), and are capable of providing base load, following or peaking capacity… Construction of [the] plants is a relatively rapid procedure – as

[15] Ibid.
[16] "Geothermal Energy", taken from the Bank's web page on Rural and Renewable Energy.

little as half a year for 0.5 to 10 megawatt units, and 1-2 years for clusters of plants with capacities of 250 megawatts or more.[17] Many high temperature resources are found in the 'Ring of Fire' which includes most countries of the Pacific Rim. Others are located close to other crustal plate margins or at rifting locations such as the Rift Valley in Africa [see Fig 6.4]. These high temperature resources offer the best potential for geothermal development." However, it is in principle available to all regions of the world.

The potential of geothermal energy is immensely greater than the quantities used so far. The useful accessible resource is resource base is 600,000 exajoules (over 1500 times world energy consumption, and a million times the amount used so far) (UNDP/WEC 2000). Its use has depended greatly on costs, which are site specific. The following are estimates based on experience with past projects:

Table 6.4: Unit Cost of Power (USc/kWh)

	Unit Cost (US c/kWh) *High Quality Resource*	*Unit Cost (US c/kWh)* *Medium Quality Resource*	*Unit Cost (US c/kWh)* *Low Quality Resource*
Small plants (<5 MW)	5.0-7.0	5.5-8.5	6.0-10.5
Medium Plants (5-30 MW)	4.0-6.0	4.5-7	Normally not suitable
Large Plants (>30 MW)	2.5-5.0	4.0-6.0	Normally not suitable

Source: World Bank Group. Web site on Rural and Renewable Energy. A 10% discount rate is assumed and 90% availability.

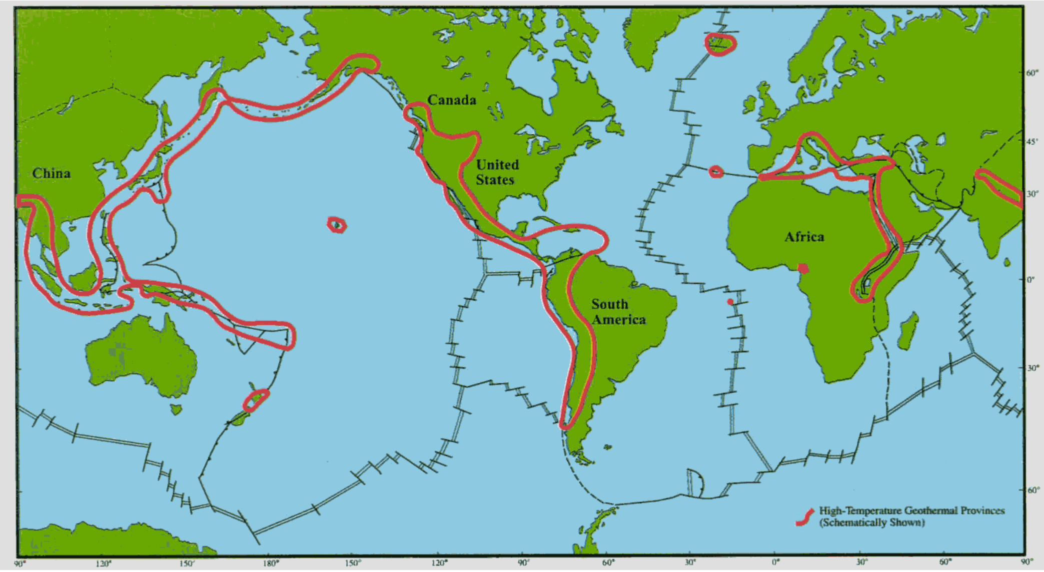
Hydro-thermal resources are easiest to exploit, typically located at depths of 1-4 km containing steam or liquid water under pressure.[18] Molten rocks (magma systems) can also be accessed at greater depths (up to 7km) as can hot dry rocks (where fluids are not produced spontaneously, but require fluid injection to extract the heat) at 4-8 km, depending on the temperature gradient; the latter are 200 times more abundant, and are "in principle available everywhere just by drilling sufficiently deep to produce rock temperature useful for heat extraction". [19] Figure 6.4 shows the location of the global high temperature resources.

[17] Source: Energy and Geoscience Institute, University of Utah, *Geothermal Brochure*, http://www.egi.utah.edu/geothermal/GeothermalBrochure.pdf

[18] The following borrows liberally from the review by JE Mock, JW Tester and PM Wright (1997), "Geothermal Energy from the Earth: Its Potential Impact as an Environmentally Sustainable Resource", *Annual Review of Energy and the Environment*, 1997, 22:305-56.

[19] Ibid.

Figure 6.4 Accessible high temperature hydrothermal resources



The main technical challenges to reducing costs and opening up this resource fall under three headings: (1) Drilling, which typically accounts for half of the capital costs. (2) Exploration and (3) Reservoir technology. Under (2) and (3) the problems are how remotely to detect producing zones deep in the subsurface, and secondly how to find better well-stimulation measures or 'heat mining' to extract the heat more extensively and efficiently.

Biomass energy

Resource, technology characteristics, maturity and costs

Biomass energy is a generic term to describe energy in the form of heat, electricity and liquid and gaseous fuels extracted from agricultural and forest residues, other organic wastes, and specifically grown crops. It currently accounts for around one tenth of world energy supplies.

Most of this biomass energy is consumed by the 1.6 billion people who lack access to modern energy forms; for whom wood, dung and crop residues are the only means of cooking and heating. Labour may be taken from farming to collect the fuel. Improving biomass uses and switching to more modern fuels for these disadvantaged groups is a feature of development policies. In addition, afforestation and land restoration projects are used as a means both to improve supplies of wood fuels to rural populations and improve the rural environment: reducing erosion and run-off and protecting groundwater resources; and improving micro-climates, nutrient supplies and thus crop yields.[20] Such projects are very important for sustaining development.

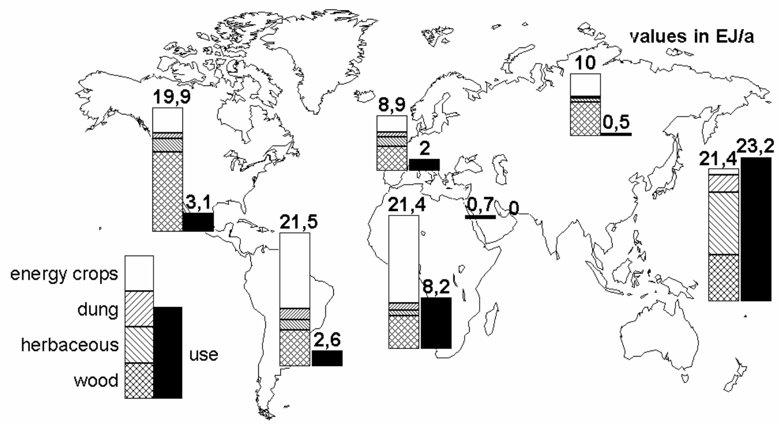
[20] World Bank (1996) *Rural Energy and Development: Meeting the Needs of 2 Billion People*. World Bank, Washington DC.

The following, however, concentrates on the use of biomass for the production of modern energy forms—electricity, combined heat and power, gaseous and liquid fuels—where it has a significant potential to contribute.

Modern biomass for heat and electricity production contributes around 4% of primary energy in the US, 11% in Austria, 20% in Finland and 17% in Sweden. Biomass for district heating and CHP is also well established in Denmark and Germany (UNDP/WEC, 2000, Bauen, 2001). Biomass already has significantly more market experience than any other emerging renewable option, (IEA, 2000b). Its use has expanded considerably in several countries in the last decade, largely as a result of supportive policy frameworks.

Most biomass energy is derived from other industries, such as forestry residues and wastes from the wood processing industry in the US and Scandinavian countries. Agricultural residues and paper pulp are also widely used in some countries such as Denmark and the Netherlands. The use of biomass for district heating and CHP has also been expanding rapidly in countries such as Austria and Germany (UNDP/WEC, 2000, Bauen, 2001). Production of biomass liquid fuels for blending with conventional vehicle fuels is well established in Brazil and the US, and a number of other industrialised and developing countries have biofuels programmes (UNDP/WEC, 2000). Figure 6.5 provides an overview of current biomass use against sustainable potential.

Figure 6.5: Biomass resources and use



Source: Bauen and Kaltschmitt, 2001

Biomass is used in several ways using a number of sources:

- For direct combustion in small and large boilers for electricity, district heating and combined heat and power (CHP);

- For gasification to produce a fuel for heat and electricity generation, and/or as a feedstock for hydrogen or liquid fuels production. There are hundreds of small-scale fixed-bed gasifiers in operation around the world, in particular in developing countries. Gasification is also becoming an increasingly popular means of treating municipal solid waste.

- For biogas extraction: Another application is anaerobic digestion—a biological process which converts solid or liquid biomass to a gas—of industrial, agricultural and domestic wastes. 'Biogas' is also increasingly derived from landfill sites ('landfill gas').

- For the production of liquid and gaseous fuels for transport. Ethanol can be produced from the fermentation and hydrolysis of sugar or lignocellulose material (e.g. woody and herbaceous residues and crops), biodiesel can be produced from the pressing and esterification of oil crops, and fuels such as DME, methanol and hydrogen can be produced via biomass gasification.

Thus biomass is a versatile and important fuel, and also a rich feedstock for the chemical industry. The potential for increased exploitation of biomass resources is very large. Biomass technologies are also undergoing continuous development both for small and large-scale applications. Expansion is planned in Denmark, Finland, Sweden and the USA, (UNDP/WEC, 2000) and several other OECD countries. There are also experiments with gasification for use in high efficiency combined-cycle power plants, which are in the demonstration phase. Currently, plants of this type are estimated to deliver energy at a cost between $0.07/kWh (a CHP scheme) and $0.12/kWh (electricity only). Engineering assessment suggests that capital costs could be reduced by half through replication and economies of scale once the plants enter early commercial application.

Much lower costs could be achieved in co-firing applications, where suitable quantities of biomass can be supplied to existing coal plants for example. The largest potential for cost reduction lies with gasification technologies, in part because of the efficiency gains over combustion plants at capacities typical of biomass electricity plants. Future biomass electricity cost from dedicated plants fuelled with energy crops could be around $0.05-0.06/kWh. Significant cost reductions have been achieved in the production of transport fuels from biomass. Improvements in technologies such as hydrolysis promise further cost reduction and increased potential in the production of fuels such as ethanol, and there is promise for competitively producing advanced fuels such as hydrogen via gasification.

Short-term market growth in biomass energy is likely to be based on the production of heat and electricity using combustion and gasification technology, including co-firing with fossil fuels, and the production of ethanol and biodiesel using a variety of sugar, starch and oil crops via commercial fermentation and pressing and esterification processes. In the medium to long-term a wider introduction of a variety of energy crops is possible, mainly woody and herbaceous perennial crops (e.g. short rotation willow and poplar coppice). Progress in hydrolysis technology could significantly increase the opportunities for widespread commercial ethanol production. Pyrolysis and gasification technologies may become commercial at larger scale as a source of heat, electricity and advanced transport fuels such as DME, methanol and hydrogen.

Biomass energy is indicated by most energy scenarios to be a key component of the global future energy mix, with significant benefits in terms of environment and development. There are significant opportunities associated with the development and commercialisation of biomass conversion technologies, the development of energy crops and their management, and the implementation of biomass energy projects.

Renewables, the grid and electrical integration issues

Renewable sources of energy give rise to a number of differences in the way in which power is fed into electricity networks and in which networks are operated, compared to the current approach, which is dominated by large and often remote 'central station' power generation feeding into the high voltage grid. These include: intermittency (variable outputs); decentralisation of generation (smaller scale generating units); and remoteness of some generation options (distance from existing infrastructures and demands).

The UK's DTI recently undertook a new study of the system costs if the UK were to secure 20% to 30% of its power from renewable sources. In addition, the technical issues for grid systems in absorbing intermittent generation were explored by utilities in several countries, and by independent analysts, in the early 1990s.

Intermittent generation

With the exception of biomass, renewable generation is both intermittent and, to a greater or lesser extent, unpredictable. This presents a number of challenges for electricity system operators, particularly if the amount of intermittent power on the system becomes substantial in relation to peak supply. Analysis in this area suggests that:

- At low penetrations (around 5% of peak supply) intermittent generators are essentially invisible to the system operator, because their output fluctuations are small compared to the normal fluctuations in demand.

- The short term fluctuation of intermittent sources is unlikely to require major changes to the operation of the grid until the penetration of intermittent renewables approaches 20% of peak supply.

- The most significant costs (which the DTI research indicates begin to arise *before* penetrations approach 20%) arise from the fact that intermittent supplies are not able to provide much of the firm capacity to ensure reliable supplies in the event of high demands and failure of other forms of generation.

Overall, and given the current small contribution of intermittent renewables to generation in almost every country, intermittency is in general unlikely to present a problem in the immediate future. However, as the penetration of intermittent renewables expands it appears likely that the potential for renewables will come to depend increasingly upon the costs and viability of a range of options for coping with intermittency – increased interconnection, demand management techniques, peaking plant and storage technologies. These options are discussed in Section 8 below.

Decentralisation

Several important options, most notably PV, but also smaller wind developments and biomass generation, are small scale and decentralised. They supply power direct to local distribution networks, close to demand.

Remote options

Renewables do not just have implications for a decentralisation of generation. The offshore options in particular are both potentially large scale and remote from both existing grid infrastructure and demands. This is likely to result in an increasing requirement for the development of new transmission capacity or new energy carriers; the issues are discussed further in Section 8 below.

6.2 CO_2 separation and storage

Resource, technology characteristics, maturity and costs

Carbon separation and storage technologies involve the separation of carbon dioxide from large scale point sources (power generation, refining, petrochemicals etc.), gathering supplies in a pipeline network and transporting them to various geological targets. These include:

- CO_2 storage with enhanced oil recovery in mature oil fields;
- Storage in producing or depleted gas reservoirs;
- Storage in confined saline aquifers

Carbon separation and storage technologies offer a medium term opportunity for significant reduction in carbon dioxide emissions with continued use of fossil fuels. Such technologies would also be a key step on the path to a hydrogen economy where, initially hydrogen would be produced by steam reforming fossil fuels.

In particular, they are important for individual countries, such as Norway and Denmark, where continued energy growth, even in the short term, has severe implication for CO_2 emissions.

World-wide the potential for storage is huge and estimates suggest that the capacity could exceed the remaining carbon locked up in fossil fuels. Geological storage of CO_2 is the most promising technology for the near term. Other options are also being investigated, including deep ocean storage. However, the large uncertainties in its prospects have led to a greater focus on geological storage.

Sequestration in depleted oil and gas fields is thought to be a secure option, in many cases, if the original reservoir pressure is not exceeded. Estimates of the prospective global capacity of such reservoirs associated with past production plus proven reserves plus estimated undiscovered conventional resources ranges from 40-100 GtC for oil fields and 90-400 GtC for gas fields. The range is wide because reservoir properties vary greatly in their suitability for storage, and because oil and gas recovery may alter reservoir formations and affect their integrity.

Deep aquifers are more widely available than oil or gas fields. They underlie most sedimentary basins, the total areas of which amount to 70 million km^2 (two-thirds onshore and one-third offshore), more than half the 130-million km^2 land area of the inhabited continents. Some sedimentary basins offer better prospects than others. To achieve high storage densities, CO_2 should be stored at supercritical pressures (more than about 75 times atmospheric pressure), which typically requires storage at depths greater than 800 m. The aquifers at such depths are typically saline and not effectively connected to the much shallower (typically less than 300 m.) sweet-water aquifers. If aquifer storage is limited to closed aquifers with structural traps, the potential global sequestering capacity is relatively limited—about 50 GtC, equivalent to less than 10 years of global CO_2 production from burning fossil fuel at the current rate. However, if structural traps are not required for effective storage, potential aquifer storage capacity might be huge; estimates range from 2,700 GtC to 13,000 GtC. For comparison, estimated remaining recoverable fossil fuel resources (excluding methane hydrates) contain about 5,600 GtC. CO_2 separation and sequestration in coal beds (with methane recovery) also holds promise, but the scale of the resource is limited

The costs of a particular method of sequestration depend on a variety of factors, such as the quality of the carbon dioxide stream (pressure, purity, temperature), plant load factor, whether it is new build or retrofit, the technology being used to separate and capture the carbon dioxide, compression required, the costs of transportation and the nature of the geologic site to be used. Typical ranges of costs are as follows:

Figure 6.6 Sequestration options

	Indicative costs \$/tonne CO2 stored	
	High end	Low end
Separation, conditioning and compression for delivery to plant boundary	65	30
Onshore gathering and transportation	7	0
Offshore deepwater injection – typical of Northern and Central sectors of the	25	13[21]
Offshore shallow water injection – typical of the Southern North Sea	3	

[21] CO_2 could be supplied at lower costs from plants where it is already captured and only conditioning and compression are required e.g. gas treatment, hydrogen and fertiliser production. Supplies from such sources are, however, limited.

Separation represents the most significant part of the overall cost. There is cost reduction potential as technology develops and experience is gained. On the downstream side enhanced oil recovery (EOR) and utilisation of existing infrastructure, of which there is a significant amount, could enhance economic benefits. For example, the North Sea has a significant potential for CO_2 storage and additional oil recovery.

In addition to costs, there are environmental objections already being raised to sequestration. For the technology to move ahead it would need to win regulatory acceptance and to demonstrate that it is a safe and effective way of reducing atmospheric CO_2 concentrations.

6.3 Nuclear Power

Fission. Nuclear power from fissile materials has been commercially available for over 40 years. In normal operation nuclear reactors give rise to negligible emissions of radioactivity. However, its development (outside East Asia) has largely stalled in the last decade. Climate change may help the technology to revive and contribute to the low carbon economy, but social and economic issues, often focussed on the issues of waste, decommissioning, safety and proliferation will need resolution if nuclear is to play a large future role.

Nuclear technology for electricity production grew rapidly in a range of industrialised countries from the late 1960s until the early 1990s. Currently it provides 17% of the world's electricity supplies, though the proportions vary widely: 75% in France, 20% in the UK and zero in a number of industrialised countries. The light water reactor emerged as the world's dominant type of nuclear technology, especially the Pressurised Water Reactor (PWR) in its US and Russian forms.

Abundance of the fissile material resource. The basic resource is uranium or thorium, which occur naturally, or the manufactured resource plutonium (Pu 239). All commercial reactors to date have used uranium as their main (usually only) fuel source.[22] There were fears of uranium shortage in the 1950s and briefly again in the 1970s. Now however it is known that uranium is an abundant element, cheaply obtainable. Conventional uranium resources will last for many decades at relatively low cost, and much more is likely to be discovered.

From the 1950s to the 1980s much effort was devoted to reactor types (fast reactors) which would need plutonium as an initial fuel, with the possibility of breeding more plutonium by using a uranium-238 blanket. This development, hugely expensive, was based on the idea that uranium would become scarce and very costly – the fast reactor might produce up to 50/60 times more energy from a given amount of uranium than a conventional (or 'thermal') reactor. However, fast reactor development is now essentially halted outside Japan and Russia (though the US is considering reviving its programmes). Fast reactors do work, but their problems are:

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[22] Thorium cycles, only explored so far to any extent in India, could in principle substitute for uranium.

- High capital costs
- Operational problems with prototypes
- Safety issues that are more acute than with thermal reactors
- Need to operate reprocessing plants, at high cost, to acquire initial plutonium, then requiring controversial and complex transport and trade in plutonium, with risks of proliferation and terrorism.

As uranium is now known to be abundant there is less economic incentive to develop fast reactors. Fast reactors and plutonium cycles are unlikely to be a source of low carbon energy in the next half century. The practical options in nuclear power for this period are all uranium-based.

Technologies. In the 1950s many experimental reactor types were explored. Surviving commercial types are mainly based on light water moderation/cooling (PWR, BWR, VVER in Russia) or heavy water types (Canada). Gas cooling has attractions but has not yet been commercially successful.

Technologies which are market-ready and embody some advances over existing plants include the AP Westinghouse/BNFL series, advanced CANDUs, the Framatome/Siemens EPR and variations on existing GE and Combustion Engineering plants (all except the CANDU are PWR or BWR derivatives). These could in principle be available for ordering very soon. However they are all large (minimum 600 MW, more often 1000MW or more), have long lead times, and have not been attractive to liberalised markets.

Other possibilities are in the design or experimental stage. The current front-runner is the Pebble Bed Modular Reactor (PBMR), a German/South African high temperature, gas-cooled reactor using ceramic fuel and with attractive safety features. It is designed to address the liberalised markets issue (unit size would be around 120MW), but will probably not be ready for market until the end of this decade.

The US has a Generation III/IV programme of reactor development designed to make a range of designs available between 2010 and 2020. France and Germany are currently pursuing the 1750 EPR (PWR-type), which is likely to fail in the market-place because of its very large size. No-one has bought one yet, even EDF in France, which is in much the best position to do so.

Recent trends. In the last ten years, investment in nuclear power has dried up in the whole of the OECD except Japan, and elsewhere only Korea, Taiwan and China have persisted with new construction. The large oil price rises of 1973/74 seemed to be the defining event that would make nuclear power fully competitive with fossil-generated electricity, but since the 1970s in the USA, and more recently in many other countries, there has been a serious decline in commercial interest in nuclear power.

The reasons for this decline are, at one level, economic – nuclear power no longer competes with alternative sources of power generation. Below the surface, however, several different forces have been at work:

- The learning effects that normally cause costs of maturing technologies to fall did not materialise, and some elements of nuclear costs increased. This was partly due to escalations of safety standards, that in turn were influenced (especially in the USA) by public disquiet and by the accident at Three Mile Island in 1979.
- The economics of other competing technologies improved substantially, especially, in the 1990s, the CCGT.
- Fossil fuel prices fell substantially after the mid 1980s, and were for a long time expected to remain low indefinitely, reinforcing the favourable economics of technologies like the CCGT
- Nuclear power became embroiled in political controversies related to safety, waste, proliferation and, more widely, public mistrust, which meant that in several countries, notably Sweden, Austria and Germany, it became politically impossible to build or commission new nuclear power stations
- The emergence of liberalisation as a major force in electricity industries in the 1990s disadvantaged nuclear – the new markets were characterised by greater risk and a higher cost of capital. This was difficult for a capital-intensive technology like nuclear power.

Overall, the political and commercial risks of nuclear power have made the technology unattractive to most investors over the last decade or so, except in the particular circumstances of East Asia, where liberalisation has come late and security of supply concerns have been strong..

R&D. Nuclear power has, like all other technologies, also suffered severe cutbacks in public funding for R&D in recent years (Japan and to a degree France being exceptions). Commercial firms that were willing to spend on long-term nuclear development up to the 1980s have also retrenched. In terms of reactor design R&D, there has been a small revival in very recent years. The US has been at the forefront with its programme to stimulate the development of so-called Generation III (and Generation III+) but especially Generation IV reactors (where Generation IV is due to be ready for market between 2020 and 2030).

Generation III reactors are a relatively conservative extension of current designs – examples are the APR (600 or 1000) series, the Advanced BWR (ABWR), Combustion Engineering's system 80+ design and the Next-generation CANDU (the NG Candu). In principle, they are ready for market now or will be in the near future. The two main principles of these new designs are simplification and greater passive safety. Also included in Generation III (or III+) is the PBMR, though it is much more radical than the above designs.

The Generation IV International Forum is led by the US but is international in scope (10 countries are involved), and has UK participation. In September 2002 the Generation IV initiative selected six broad technology types from an overall 'road-map' for future cooperation. Generally there is now a concentration on relatively smaller unit sizes, as these are likely to be more market-friendly,[23] and advances are

[23] M. Grimston and P. Beck (2002) *Double or Quits? The Global Future of Civil Nuclear Energy* Royal Instiute of International Affairs/Earthscan, especially Chapter 6.

sought in economics, safety, reliability, proliferation resistance and waste minimization. The six agreed technology types are still defined at broad level but all promise to be radical compared to today's technology. The six system types are: gas-cooled fast reactors systems; lead alloy liquid metal-cooled reactors; molten salt; sodium liquid metal-cooled reactors; supercritical water-cooled reactors; and very high temperature gas-cooling.

While technology development will lead to learning effects for nuclear power, the quantitative importance of learning has been substantially less for nuclear power than for other low-carbon technologies. Learning rates for nuclear power as low as 5.8%[24] have been reported historically, against 10% to 20% for most other energy technologies. While such results must be interpreted with care, there are several reason why learning may be expected to be slower for nuclear than other, small-scale low carbon technologies. These are

- Learning rates tend to slow as technologies mature. The fundamentals of nuclear power are well established and the technology has a 50-year history of intensive development.
- The long lead times for nuclear projects mean that improvements derived from feeding back earlier experience into later design are necessarily slower
- The need for safety licensing of nuclear designs means that additional time may be needed to incorporate earlier technological lessons into later designs
- The scope for economies of large scale manufacturing production is less for nuclear power, where unit sizes are large, than for emerging options such as fuel cells and many renewables, where hundreds or thousands of units may be built

The industry. Because there has been so little new investment activity in recent years in the OECD, the nuclear industry has shrunk and consolidated. There are now two main independent groups capable of reactor design and construction: BNFL/Westinghouse/ABB and Framatome/Siemens, now led by Framatome. Japanese companies such as Mitsubishi, Hitachi and Toshiba have been involved closely with technology development but do not have independent design capability. In the fuel cycle there are tow dominant groups, BNFL/Westinghouse and Areva/Cogema, though in the USA other players (eg the US Enrichment Corporation, now privatised, are also significant).

Costs. The costs of nuclear power in current market conditions are uncertain in many countries, because of lack of recent experience. However countries reporting to the Nuclear Energy Agency of the OECD recently reported an expectation of construction costs (the dominant elements in nuclear costs) between $1500 and $2500/kW. This compares to around $600-$700/kW for CCGT construction. The US DoE nuclear programme aims at a capital cost around $1000/kW, at which point nuclear might

[24] McDonald, A. and Schrattenholzer,L. (2001) 'Learning rates for energy technologies', *Energy Policy* 29, 255-261.

become competitive in the market place again. At present nuclear generating costs, for newly constructed plant, are most likely to be around 5.5c/kWh with prospects of reductions to 4.5c/kWh.

For the future, a widespread use of carbon taxes and/or emission trading, in recognition of the carbon-free status of nuclear generation, would clearly help the economics of nuclear power.

Environment. While nuclear has zero carbon emissions at the point of use, it also gives rise to other, unique environmental issues. The foremost among these is nuclear waste, where politically acceptable solutions are not yet visible (except possibly in Finland and more speculatively the USA). The basic issues are the longevity of radioactivity and the lack of public trust in solutions proposed by the industry. In addition, there are serious concerns about nuclear proliferation. These are especially intense where reprocessing of nuclear fuel takes place, creating separated plutonium, a direct bomb-making material. It may well be that a condition for the future use of nuclear power on a larger scale will be the renunciation of spent fuel reprocessing for non-proliferation reasons.

Waste and decommissioning. The failure to resolve waste issues continues to bedevil the prospects of the industry.[25] The issues are less technical than political/social, though this too is an area where innovation could reduce the scale of the problem and the costs significantly.[26] All prospective nuclear technologies produce some waste (including fusion, due to the probable need to use deuterium/lithium cycle) and so waste is an issue universally. It is possible that in the post-September 11 climate, technical proposals for underground monitored/retrievable storage will prove more politically and socially acceptable than in the past. Nevertheless a major pre-condition for an expanded worldwide contribution of nuclear power to low carbon developments will be resolution of waste issues at the political and social level.[27]

Fusion. Fusion has been a great aspiration of scientists since the early experimental reactors of the 1950s, though it has still not reached the point where sustained net electricity can be generated – in other words the power input to fusion still generally exceeds power output . A report of the US President's Commission of Advisors on Science and Technology (PCAST, 1999) summarised the situation as follows:

"Nuclear fusion offers a more distant possibility of abundant energy free of greenhouse gases and conventional air pollutants. Even under favourable assumptions about fusion R&D investments and outcomes, it is not likely to be able to deliver a significant contribution to world electricity supply much before the middle of the 21st century. But uncertainties about the ultimate tractability of the problems of fission, combined with the possibility that fusion will offer significant advantages in safety, waste characteristics and proliferation resistance, make it prudent to pursue the R&D needed to determine whether fusion's promise can be realized. Fusion R&D has

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[25] Early reports of UK Royal Commission on Environmental Pollution (RCEP) (Flowers' Report) in 1976, Yucca mountain studies and others.

[26] UK CSA, 2001.

[27] There are important spatial issues here (e.g. can we find 'safer' international solutions but with much more nuclear transport, or should we go for local solutions with less transport problems but more variable safety/quality implications). Russia is a critical player in this area.

embodied a steadily growing international collaborative component since 1958 … in part by being so costly as to make cooperation a necessity. But (notwithstanding the recommendations of PCAST studies in 1995 and 1997) the US Congress in the last few years has been unwilling to allocate to fusion R&D the sums that would be needed to maintain both a solid domestic program and significant US participation in the flagship international fusion effort—the International Thermonuclear Experimental Reactor (ITER)."

There has since been some revival of interest in the US, though ITER, a joint Europe/US/Russia/Japan project still under negotiation, has been estimated to cost $6-10 bn Meanwhile experiments using the previous generation Joint Experimental Thermonuclear (JET) project at Culham in the UK are being extended.

The feasibility of fusion in next 50 years is thus unclear, though many scientists argue for a continuation of R&D in this area. Some commentators have suggested that a commercial device might be technologically feasible within the next 25 years (though most estimates still point to 40-50 years[28]), and has suggested *inter alia* a research programme in advanced materials such that much higher temperatures, necessary for fusion to be a reality in the magnetic confinement route, could be managed.

[28] UNDP/WEC *World Energy Assessment* (2000)

7. Reducing primary energy demand through greater efficiency: Improving efficiency in energy conversion, transportation and use

All studies that explore the possibility of achieving deep cuts in CO_2 emission indicate that it doing so is difficult, perhaps impossible, without efforts to improve energy efficiency. Energy efficiency is also free of most non-carbon environmental impacts and brings strong benefits for other policy goals, such as security of supply and expanding the benefits of access to modern energy. We consider some of the main options in this sub-section.

Resource

Energy efficiency improvements could make a very substantial contribution to CO_2 emissions reduction – for example, in OECD countries a reduction of 30% on current levels is cost effective based on current technologies and the theoretical improvement potential is much greater – without reducing the quality or quantity of energy services provided. In many cases, particularly in the end use sectors, a variety of barriers have historically impinged upon the adoption of mature and proven technologies that are cost effective. Addressing these is likely to be of high importance in the short to medium term, but this issue is beyond the scope of this report.

7.1 Advanced fossil fuel energy conversion technologies

Technology characteristics, maturity and costs

There are three ways by which the fossil fuel industry might respond to climate change. The *first* is through efficiency improvements to energy conversion technologies for electricity supply; the *second* is through improvements in distribution and transmission. Finally, it is possible to separate hydrogen from carbon at source (considered in the next section).

Gas-fired power stations. Natural gas combined cycle gas turbines (CCGT) are highly promising for emissions reduction in the near term, as they were in the 1990s. Fuel switching from coal to gas almost halves carbon dioxide intensity – from around 850 g/kWh to less than 500 g/kWh – due to the lower carbon content of gas and the higher efficiency of gas-fired CCGT stations.

They have important advantages over other options: short build times, high efficiency, low levels of local pollutants, and low installed capital cost. They are also attractive over a wide capacity range (megawatts up to hundreds of megawatts). CCGT has therefore become the preferred technology for new electricity capacity additions in the United States and Europe, enjoying a significant economic advantage over new coal plants.

Future improvements focus around increasing both gas and steam turbine efficiency, the so-called 'top-hat' cycle could raise efficiencies up to 70%. In the long term, CCGT could evolve towards large fuel cells with heat recovery (fuel cells are discussed further below).

Advanced coal technologies. Emerging technologies have the potential to reduce carbon intensity of conventional coal fired steam cycles by over 50%. When used for

CHP, efficiencies of >80% are possible with a reduction in carbon intensity of up to 75%. This is of particular importance in the context of India and China, which are likely to remain heavily dependent upon coal for many decades.

A range of options are emerging, the leading technologies are various forms of supercritical pulverized fuel designs – which can raise efficiencies to around 50% - and integrated gasifier combined cycle power plant, believed by many to be the most innovative prospect for the long term. IGCC systems combine two established technologies: coal gasification for the production of synthesis gas (a gas mixture containing mainly carbon monoxide and hydrogen) and CCGT power production. Synthesis gas (syngas) obtained from the coal gasifier is used to drive gas turbines. The exhaust gas is used to generate steam that is converted to electricity by a steam-turbine cycle.

Demonstration projects using IGCC technology are operating or under way worldwide, but the technology has not been widely deployed. Efficiencies in demonstration projects (two in Europe and three in the United States) are about 40 – 43%. In the long term, efficiencies of greater than 60% are thought possible. IGCC has the very important advantage that sulphur is removed pre-combustion, avoiding the need for costly scrubbing equipment, and NOx and particulates are reduced dramatically. These are of great importance to China, India and other countries still struggling to reduce local air pollution from the power sector.

In the near term IGCC technology is not competitive with gas CCGT or with large pulverized coal power stations. Considerable cost reductions will be required. In the medium to long term, however, it could play an important role in an evolutionary path towards near zero emissions with low cost fossil fuel reserves, *if* coupled with hydrogen production and carbon sequestration.

7.2 Loss reduction in electricity transmission and distribution.

Power system component development to reduce losses from transmission and distribution systems offers significant opportunities to reduce greenhouse gas emissions. Developments in power electronics – including wide-band semiconductors for high-power switching devices and advanced converter designs – are needed to improve power management on existing systems and to enable high-voltage direct-current (DC) transmission for long-distance power transfers. In the longer term superconducting technologies could dramatically improve the efficiency of long distance transmission. Another route is decentralised electricity generation, discussed below.

7.3 Fuel cells

Technology characteristics, maturity and costs

Fuel cells convert hydrogen and oxygen directly into electricity. They are highly efficient, clean and quiet, with no moving parts. They are promising technologies for reducing greenhouse gas emissions in the decades beyond 2010, and have the potential to become a ‘disruptive’ or ‘transforming’ technology, for both electricity generation and transport. They have three major advantages:

- *Energy efficiency*. In power generation, for example, an advanced solid oxide fuel cell (SOFC)/gas turbine system is expected to operate at more than 70 percent electrical efficiency, producing only 50 to 70 percent of the CO_2 emitted from current CCGT plants. Fuel cells also have the potential for a two to threefold efficiency gain when used for transport – again when compared to existing vehicles.

- *Low or Zero CO_2 Emissions*. Fuel cells are a key technology in an evolving strategy to a low carbon economy. They are a complementary technology to hydrogen as an energy carrier (see below).

- *Very low emissions of local air pollutants* – whatever the fuel, fuel cells largely eliminate oxides of sulphur and nitrogen and particulates – all of which continue to be associated with conventional engines.

However, current costs are well above conventional technologies in most areas, though this varies with the type of fuel cell: estimates range between $2000 and $10,000/kW (a mature technology such as a gas turbine costs about $400-600/kW, a car engine $50/kW).

There are five main classes of fuel cell, each with differing characteristics:

- The Alkaline Fuel Cell (AFC, with an operating temperature of 60-90^{o}C)
- The Solid Polymer Fuel Cell (SPFC; operating temperature of 80-100^{o}C)
- The Phosphoric Acid Fuel Cell (PAFC; operating temperature of 200^{o}C)
- The Molten Carbonate Fuel Cell (MCFC; operating temperature of 650^{o}C)
- The Solid Oxide Fuel Cell (SOFC; operating temperature of 800-1000^{o}C)

Each has their advantages and disadvantages. The low temperature fuel cells generally incorporate precious metal electrocatalysts, exhibit fast response and short start-up times, are available commercially or are near commercialisation, but require a relatively pure supply of hydrogen as catalysts can be poisoned by carbon monoxide. The higher temperature fuel cells, in contrast, can be directly operated on a range of light hydrocarbon fuels (as the high temperatures allow reformation within the cell itself), do not require expensive electro-catalysts, and generate useful heat. They are well suited for CHP or for integration with combined cycle gas turbine power systems. However, they have long start-up times, reliability is still a concern (partly on account of the high operating temperatures and subsequent thermal cycling issues), and are only at the demonstration stage.

This summary is, of course, a simplification. For example, there is on-going research to develop intermediate temperature devices which operate at 500^{o}C. Nevertheless it is reasonable to distinguish between the low temperature variants, which are best suited to transportation, and the high temperature variants, which are best suited to electricity generation and CHP.

Progress and prospects

Engineering analysis and the modularity of the technology both suggest they have the required characteristics for rapidly declining cost or 'learning curves' as the volume of applications expands and as research, investment and operating experience accumulates.

It is not possible to give a more detailed review of fuel cell technologies in this report. But with further development and once in mass production it is estimated that they could cost as little as $30/kW for transport and $300/kW for stationary power. Table 7.1 gives an indication of current costs of the technologies and those predicted for mature systems by the companies involved.

Table 7.1: Recent and Projected Costs of Fuel Cell Systems ($/kW)

	AFC	**SPFC-stationary**	**SPFC-transport**	**PAFC**	**MCFC**	**SOFC**
Cost in 1999	2000	8000	550	3000	5000	10,000
Predicted long-term cost	50-100	300	30	1000	600	600

We return below to fuel cells in the context of their potential applications – in improving efficiency in vehicles and in the emergence of small scale decentralised electricity generation with expanded use of combined heat and power (CHP)

7.4 Improving efficiency in end use: industry, buildings, appliances and vehicles

Industry

Some key areas of technology development for industrial energy efficiency are:

- Low temperature processing – using catalysis, biotechnology or nanotechnology
- Process change to eliminate heating cycles, e.g. powder metallurgy – these can often have 'near net shape' benefits too so that there is less material waste
- Materials change – such as composites where plastics replace metal, or possible alternatives to cement
- Materials technology – can facilitate high temperature heat recovery and high temperature insulation as well as turbine technology.
- Control technology – useful in motive power reduction, such as variable speed drives

Some of the most spectacular productivity improvements in primary energy use over the last decades have been in the process industries where an engineering technique sometimes called process integration has been applied to multi-stage processes. This explores the options for using the waste products and heat from each stage as an input for another step in the total process. When applied to an industrial economy as a whole this analytical technique suggests that something like 30% of the primary energy consumption could be saved before any change in end use technologies. The use of waste heat from power stations in large-scale CHP schemes is a commonplace example of the approach – note that options for small scale CHP are also emerging; they are discussed below.

Technology options

New process plant design exploits process integration techniques to the full, often saving 30-40% of energy over non-integrated processes. Large scale CHP generation technology enables waste heat from power generation to be utilised in other commercial activities nearby, where it is possible to site new power developments such that they can help meet heat demands. It raises the overall efficiency of primary energy use to around 80%. Heat pumps (air conditioning units fitted in reverse) provide similar efficiencies in primary energy. They are particularly suited to use with heat sources that are a few degrees cooler than delivery temperature. Developments in catalyst technology offer the prospect of reducing the overall need for high temperature processes and therefore wider use of waste heat. Thermal insulation reduces the heat lost to the environment.

Technology characteristics, maturity and costs

Process integration is now a relatively mature technique, though its use is still being explored in specialist process industries. Heat pumps and insulation materials draw on a mature technology. In contrast, catalyst technology is expanding rapidly as new investigative techniques give greater understanding of the underlying mechanisms.

Progress and future prospects

The basic technologies are relatively mature. In the context of electricity generation, large CHP and heat pumps are potential competitors to displace direct electric space heating in contexts where fossil fuel cannot be supplied to the building. CHP has important opportunities in the expanding cities of the developing world, where the district network can be laid at the same time as other services. Innovation relates to their incorporation in end use applications rather than in further definition of the product. Micro-CHP is a new technology exploiting advances in power generation technology to integrate power generation with a domestic boiler, and could be economic for some installations within a decade. Catalyst technology still has far to progress.

Buildings and commercial and domestic appliances

The range of options in this area is very broad. Most building energy use is heating (and cooling in some countries), so fabric and heating technologies are of great importance. In addition, however, appliance (electricity) use is growing fastest in many countries and so improvements in this area are also important and we return to them below. Much can be done with existing technologies, but there is still scope for innovation to expand the scope of what is possible. In buildings the main areas with scope for improvement include:

- Cheap retrofit wall insulation
- Superinsulating prefabricated wall modules
- Low conductivity glazing
- Economic heat pumps
- Effective micro-CHP – both Stirling engines and fuel cells.
- Passive cooling design
- Improved appliances and lighting equipment

Many, such as improved domestic insulation are mature and cost effective, and some are relatively 'low tech'. Most are not adopted as widely as their low costs might suggest due to a variety of market and non-market barriers. Addressing such barriers is discussed elsewhere (PIU 2002a) and is of particular importance in reducing carbon emissions in a cost effective way.

For the purposes of this report we highlight a limited number of promising technology areas to illustrate the potential.

(a) Lighting Technology

Resource

Daylight levels are several times higher than the requirements within a building. Artificial lighting in daytime can be both a waste of energy and add to the cooling load of an air-conditioned building. The overall cost of lighting in a deep plan air-conditioned office might be 40% of its total after allowance for cooling load. Effective and efficient lighting at night is one of the first uses to which electricity is put in developing countries, increasing productivity. Lighting energy may account for around 5% of national primary energy consumption.

Good building design can dramatically reduce the demand for artificial lighting during daylight hours, without leading to problems of glare and unwanted solar heating. The 'technologies' here surround effective architecture and planning. In addition to the importance and potential of architectural aspects, lighting technologies themselves also hold great promise:

Technology Options

Most developing countries are able to manufacture and deploy modern discharge lamp technology. Over the last century this development has seen a 50 fold improvement in efficiency yet with a significant an improvement in lighting quality. New technology is based around the light emitting diode.

Technology characteristics, maturity and costs

LED technology is already in use in signalling and display lighting industrial applications. Apart from operating at near room temperatures LED's have a very long working life, that in commercial applications is likely to compensate for their cost. There is little experience of their use in more general lighting contexts.

Progress and future prospects

The technology is getting close to providing a lighting source of sufficient quality for use in buildings. It would be expected to be taken up first in commercial applications because of its very low maintenance cost and offset of air conditioning costs.

Daylighting: 'Light pipes' are a means of bringing daylight into areas of buildings without good access to windows or sky-light. Utilising flexible tubes with highly-reflective internal coatings, daylight can be brought substantial distances from roof or external walls. Daytime electric lighting needs can be reduced sharply in both commercial and residential applications.

(b) Appliances

A wide range of improvements to domestic and commercial appliances are possible, many at low incremental costs; in particular efficiency improvements available now for boilers and 'white goods' such as fridges can lead to large reductions in energy use. We highlight here another example of energy inefficient design that could be easily overcome with better technology at low cost. Most modern consumer electronic appliances – computers and audiovisual equipment in particular – require that power is transformed to low voltage (LV) direct current (DC). Many also require low levels of electrical input when not in use, to power 'memory' chips for example, or to enable remote operation. Such power is often referred to as 'standby' loads.

Taken individually, such loads consume small amounts of power, but collectively and on a global scale the aggregate demand for power is significant. It has been estimated that such loads total around 10% of residential electricity demand. In the OECD as a whole this results in energy wastage of around 15 GW, equivalent to the output of 15 – 20 power stations, or 24 million European size cars (IEA 2002a).

The opportunities for consumers to 'switch it off' are decreasing; more and more appliances need a constant (very low level) supply. But the potential for technology to reduce such loads is tremendous. Standby power supplies can consume between 5 and 30 Watts each – equivalent to a typical LV ceiling spotlight – and many households have several such devices, all 'leaking' electricity invisibly (in the form of low levels of heat). However Sony recently developed a system able to provide full standby and memory services, with no loss of consumer benefit, using electronics that consume just 0.1 Watts.

The incremental cost of such efficient design, relative to the overall cost of electronic appliance manufacture, is negligible. As the turnover and proliferation of electronic goods is very rapid the integration of better designed standby power provision offers the potential for considerable gains in a very short time.

This is an obvious example of end use technologies that are more efficient, cost little or nothing more than less efficient alternatives, and could and should be adopted as soon as possible. There are numerous others.

Transport

It is possible to make several types of technological improvements in vehicles:

- advanced internal combustion engines

- improved vehicle design such as light weight materials and aerodynamics
- electric, hybrid and fuel cell drivetrains

There is another—perhaps more important—means of improving efficiency in transport, namely the development of transport management systems including congestion policies and electronic tolling and signalling. The latter are however beyond the scope of this report.

Advanced Internal Combustion Engines and improved vehicle design. There have been significant technological advances in the ICE during the past three decades; yet the potential for technology to reduce still further the environmental impact and improve the efficiency of conventional vehicles is far from exhausted. Advances in diesel engine technology in particular are expected to deliver substantial improvements to the efficiency of the vehicle fleet in coming years (partially through refinements that improve the attractiveness of diesels in the car market). In addition, lightweight materials, reduced rolling resistance, better lubricants and further improvements in aerodynamics can make important contributions to efficiency gain.

Applications of these technologies do not cause a fundamental change in the “conventional character” of the vehicle. It will still run on an internal combustion engine and will still use a conventional drive train and a conventional vehicle configuration. Taken together these improvements are widely expected to enable manufacturers to meet their voluntary commitment to the EC to reduce emissions from their fleets by 25% in 2008.

Electric and Hybrid Vehicles. Hybrid electric power trains for vehicles promise large emissions reductions in the near to medium term. Current hybrids, such as those made by Toyota and Honda, switch between electric and conventional drive to so that the IC engine use is optimised, shut off the ngine in traffic and low speed use and use on over-run, and use flywheel inertia and braking for battery charging. But the engine is not for battery charging alone and remains part of the drive train. In the longer term hybrid vehicles are likely to use electric motors alone for traction, with a small IC engine running for battery charging. There are two advantages: (a) a significant improvement in fuel efficiency. Hybrid vehicles achieve the improvement in efficiency by allowing the battery and electric motors to take the power surges such that the engines can run more smoothly near their optimum operating conditions. (b) An appreciable reduction in local air pollutants. Hybrids, together with some of the improvements to vehicle design mentioned above, could lead to an improvement in efficiency of around 50% for the average passenger car by 2020.

Fuel-Cell-Powered Vehicles. Fuel-cell-powered vehicles hold the potential for reducing transport emissions enormously in the medium to longer term. The auto industry is working to have general market fuel cell cars from around 2015 - 2020, with buses and utility vehicles available sooner. The benefits of fuel cells were discussed above. In the short term, vehicle power systems may also include a fuel processor and a power conditioner unless hydrogen is provided directly and stored onboard. The fuel processor converts fuels, such as natural gas, methanol, gasoline or bio-ethanol, into the hydrogen-rich fuel required by the fuel cell. Fuel cells may also be operated as hybrids, with small batteries to enable efficiency improvements – for example through regenerative braking.

With hydrogen as its fuel, the only emission stream from a fuel cell is water vapour. When a fuel cell uses methanol or hydrocarbons as its fuel, reforming them to obtain hydrogen will produce CO_2 and other pollutants as by-products (and reduces ‘well to wheels’ efficiency to a level similar to that of an ICE-hybrid; see below).

In the long-term, the combination of advanced fuel-cell technology and an infrastructure for supplying low carbon hydrogen – or strengthened gas or electricity infrastructure to support localised production of hydrogen - offers the potential for a largely pollution-free propulsion system. The lack of adequate infrastructure and of high density on-board storage technologies for hydrogen are the greatest obstacles to its use as a transport fuel – an issue returned to below.

The gains in energy efficiency associated with fuel cell and hybrid-electric vehicles deserve emphasizing. Transport now accounts for roughly one quarter of energy consumption. ‘Well to wheels’ efficiency allows for all losses arising between the extraction of the primary energy source to when it turns the wheels of the vehicle. For gasoline engines it averages about 14%, for diesel engines18%, for near term hybrid engines 26%, for the fuel cell vehicle 29%, and for the fuel cell hybrid vehicle 42%, a 2-3 fold increase in efficiency relative to vehicles today. Fuel cells can more than double the efficiency of an ICE, but energy is used in making and storing hydrogen; IC-hybrids do not offer quite such dramatic engine efficiency gains, but avoid some of the upstream losses. As a result, a two-fold increase in the fuel efficiency of private vehicles appears feasible in the medium term from *either* technology, with hybrids penetrating the market substantially within 20 years. And a longer term shift away from carbon based fuels altogether is possible, once we can develop enough low carbon hydrogen.

Aviation: Scenarios of the IPCC and others show aviation’s share of emissions increasing very substantially, because of huge expected expansion of air travel, because air travel is fuel intensive and because reductions are likely to be more difficult in this area than others.

The challenges for aviation are particularly acute. Fuel costs are a very significant component of aviation costs, and as such the aircraft and engine industries have already done much to optimise efficiency. Furthermore, fuel weight is a more significant parameter of aircraft performance than it is for land-based transport, and so moves to alternative fuels are heavily constrained by problems of low energy-density for many alternatives to kerosene. The Royal Aeronautical Society has said it would expect the cost of saving an equivalent tonne of CO_2 in aviation to be many times more expensive than in other sectors.

Emissions may be reduced in three ways:

- changing operating practices: for example reducing speed and possibly cruise altitude;
- aircraft redesign: for example blended wing-body or ‘flying wing’ designs and boundary layer control offer significant efficiency benefits;

- substitution by alternative fuels; for example, biomass-derived liquids or hydrogen.

Given the difficulties and long lead times for changing designs, interest is growing in finding alternative fuels. Biomass resources are a focus. Forms of biodiesel in particular have the potential to be mixed with kerosene as ‘extenders’ – overcoming some of the technical limitations of pure biomass fuels. In the medium term, synthetic forms of kerosene are possible, based on biomass processed through the Fischer Tropsch process. Costs are currently high, but there is significant room for development.

In the long term hydrogen is a potential aviation fuel, as it is for land-based transport. This would require significant redesign of engines and aircraft (due largely to the lower volumetric density of hydrogen and hence larger storage tanks needed), but would offer many of the attractions discussed in the context of road transport.

8. New energy systems and facilitating technologies

The development of low carbon energy systems will require innovations that go well beyond developments of the component technologies themselves. There will be a need to reconfigure the infrastructure so that the technologies can be operated reliably, such as with the use of fuel cells and small scale renewable energy technologies in the electricity distribution networks. In other cases, such as with fuel cell vehicles, the supply of hydrogen fuels to the service stations will be an issue. The introduction of hydrogen itself would be a transforming event for the electricity and gas industries, and would increase coupling between the two. Finally, especially if decentralised forms of heat and power were to emerge, we may see electricity grids having to shift from the management of, typically, 50-100 large power stations, to the management of literally millions of small-scale generators and controllable loads. All this will mean far-reaching changes in the ways energy systems evolve and are managed and operated.

8.1 Energy storage

As noted above the intermittent nature of renewable energy supplies is not a serious *technological* constraint on their development in the near- to medium-term. Up to perhaps 20 percent of the demand for electricity could be met by 'intermittent' renewable energy without the need for major changes to electricity systems. However, whilst load management and peaking plant for higher levels of market penetration could enable the penetration of renewables to continue, a solution to the storage problem is highly desirable. It will be essential if the use of renewable energy for transport is to expand on a substantial scale.

Storage also improves the economic returns to investments in fossil fuels and nuclear power. Decentralised storage systems may also reduce losses, reduce the need for reinforcements of the transmission and distribution systems, and facilitate voltage control.

On a moderate scale, and for storage across periods of hours to days, there have been some successes. One is the storage of the outputs of base load nuclear and high efficiency fossil-fuel stations in pumped-storage-hydro systems – but it is notable all such systems were constructed under conditions of state owned monopoly. The very high capital costs associated with such systems make their construction less attractive under liberalized markets. A more recent and promising example is the regenerable fuel-cell system ('Regenesis') introduced by Innogy.

However, storage of energy on a major scale and for longer periods has proved difficult. It remains much more expensive than energy stored in fossil fuels. Developments in storage systems are therefore fundamental for the future of the energy industry. They would open the gate to very wide deployment of renewable energy and a zero carbon economy. All the above technologies, however, are proving difficult to develop, with the exception of pumped hydro, which is limited by the availability of sites. This is why the hydrogen option is so important. Options for further development include:

- Batteries. (Small scale, short-term storage.)
- Advanced ultra high speed flywheels. (Small and medium scale, short term storage.)
- Pumped storage. (Large-scale, short-term storage.)
- Compressed air storage. (Large-scale, short-term)
- Thermal storage. (Small and medium scale, short term storage.)
- Thermo-chemical storage. (Short- or medium-term storage, medium scale.)
- Superconducting magnetic storage.
- Electrical 'supercapacitors'. (Small-scale, short-term storage.)
- Electro-chemical storage in electrolytes (Intermediate scale)
- Hydrogen production and storage - discussed below

All of the above are technologically feasible and in most cases have been demonstrated. Most are in use for special purposes. The key issue is technical development and innovation in order to reduce costs. Data on costs are scarce and often rely on engineering assessments and projections. Some estimates are provided in Table 8.1.

Table 8.1: Capital Costs for Electricity Storage (1997 Dollars)

Technology	Component of Cost:		Total Capital Cost, $/kW	
	Discharge Capacity, $/kW	Storage, $/kWh	2 hour storage	20 hour storage
Compressed Air:				
• Large (350 MW)	350	1	350	370
• Small (50 MW)	450	2	450	490
• Above ground (16 MW)	500	20	540	900
Pumped hydro	900	10	920	1,100
Battery (targets):				
• Lead acid	120	170	460	3,500
• Advanced	120	100	320	2,100
Flywheel (target 100 MW)	150	300	720	6,200
Superconducting magnetic storage (target 100 MW)	120	300	720	6,100
Supercapacitors (target)	120	3,600	7,300	72,000

Source: US President's Committee of Advisors on Science and Technology. Washington D.C., 1999.

8.2 The changing nature of electricity grids

The emergence of high efficiency small scale generation technologies (fuel cells, microturbines), small CHP and the controls required to operate the electricity grid with large numbers of such units in place would change the nature of electricity provision. Small scale and modular, such technologies have great potential to secure economies of scale through bulk manufacture – shifting electricity generators away from their traditional preoccupation with gaining economies of scale through large power plants. Such changes would also suit the investment criteria of liberalised markets, offering short build times, low capital investment and flexibility of operation.

Increased use of decentralised generation offers the potential to reduce transmission losses and, if technologies are used in CHP-mode, to substantially improve overall energy efficiency. It may also offer a route to modern energy service provision in parts of the developing world, in the form of town or village-scale 'mini-grids' (see below). Finally, the development of techniques to actively manage local distribution networks may facilitate wider adoption of some renewable technologies such as wind and PV. Decentralised generation is likely to be of considerable importance to the future development of electricity supplies.

8.3 Hydrogen production, storage and use

Technology characteristics

Hydrogen is not a source of energy; it is a carbon-free energy carrier that has many potential applications, including vehicle fuel and centralised or distributed electricity generation. It can be used in modified boilers, engines and turbines, or in fuel cells.

Interest in hydrogen has five main drivers:

- Hydrogen burns cleanly, with no emissions of local air pollutants - use as a vehicle fuel would eliminate air pollution problems from car exhausts.
- It offers the prospect of zero CO_2 emissions for a wide range of uses. The level of CO_2 emissions reduction compared with conventional technologies and fuels will depend on how the hydrogen is produced and used. When it is produced via electrolysis of water using nuclear or renewable electricity, CO_2 emissions are very low indeed (as discussed above). It can also be produced directly from fossil fuels, with the carbon being sequestered.
- As discussed above, use in fuel cells can lead to efficiency gains.
- It can act as an electricity storage medium
- Because it can be made from many sources it can improve security and diversity of supply

Technology maturity and costs

There are two main elements in the hydrogen cost equation: the cost of manufacture and the cost of distribution to the end user. The equation is further complicated by the choice of whether to make hydrogen centrally and distribute—either as a high-pressure gas, stored in a convenient medium, or as a liquid—or to make it on-site in small plant. This provides a number of possible pathways to examine.

Manufacture. Because of its presence in so many compound forms it is possible to make hydrogen from all hydrocarbon fuels, biomass and water. Processes to do so are all technically feasible, though many of them are currently expensive.

In the short term, producing hydrogen from natural gas by steam reformation is often the cheapest method and one of the cleaner methods involving hydrocarbon-based processes. In the medium term, biomass gasification offers production at a competitive cost if current developments can be brought to commercialization. In the longer term, the production of hydrogen by electrolysis from renewable energy will certainly offer an environmentally satisfactory means of producing hydrogen.

Yet another possibility is the direct production of hydrogen from water using solar energy and catalysts, a technique known as photo-electrolysis. This would have the advantage of combining two stages in the production of hydrogen—electricity generation and electrolysis—into one, with prospects of reducing costs and improving conversion efficiencies. More esoteric forms of production using bacteria and algae are also under consideration and would be equally non-polluting. These approaches are very much at the laboratory stage and require much further R&D.

Table 8.2: Current and projected costs of gaseous hydrogen (ca 20 bar) $/GJ[29]

	Near term	**Long term**	*Comment*
Renewable sources			
Hydrogen from biomass gasification - large plant (18,000GJ/day ca 60MMscfd)		7-10	Technology still remains to be demonstrated on a commercial scale. Assumes fuel cost in range $2-4/GJ
Electrolytic Hydrogen (180 GJ/day)			
Solar PV	24-41	15-25	
Wind	20-45	17-25	
Solar thermal SW US	45-75	25-35	
Off-peak hydroelectricity	10-20	10-20	
Fossil Sources			
Steam Reforming natural gas • Large plant (18,000GJ/day ca 60MMscfd or 144 tonnes/day • Small plant (180 GJ/day - ca 0.6MMscf or 1.4 tonnes /day)	4-7 11-14	4-7 11-14	Assumes a gas price of $2.5/GJ for large plants and $4/GJ for small plants 45-60% projected H2 costs due to natural gas with capex ca 40% - long term. H2 costs driven primarily by outlook on natural gas prices - compact processors would yield costs close to the low end of the range for small plant.
Coal gasification • Large plant (18,000 GJ/day) • Medium plant (9,000 GJ/day)	9 13		Assumes coal prices at $1.5/GJ
Residue/coke gasification • Large plant (18,000GJ/day)	7-11		Assumes coke and residue prices at $ 1.4-2.7/GJ

29 Based on Lipman and DeLucchi, 'Hydrogen-fuelled vehicles', *Int J of Vehicle Design*, 1996, Berry, *Hydrogen as a Transport Fuel: Costs and Benefits*, Lawrence Livermore Laboratory, 1996, and the IEA *Automotive Fuels Survey* 1997. See also Gregoire-Padró and Putsche, *Survey of the Economics of Hydrogen Technologies*, National Renewable Energy Laboratory, 1999.

Storage and Transportation. In the long term transporting hydrogen is likely to be based upon pipelines. This will require a considerable investment in infrastructure and is unlikely to be achieved in the short term. In the near term there are a variety of pathways by which hydrogen could be delivered to the end user.

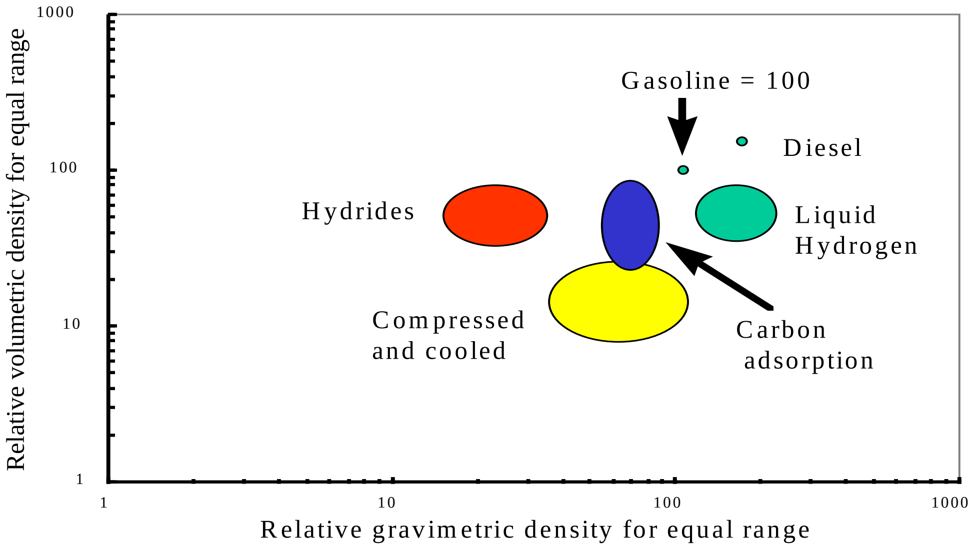
- Central manufacture and distribution:
    - As a cryogenic liquid
    - As a gas in high pressure containers
    - Physically adsorbed or combined as a liquid hydride
    - Central manufacture of a hydrogen rich carrier from which the hydrogen can be easily recovered at the local re-fuelling site
- Manufacture by local electrolysis of water using off-peak electricity
- Local production from natural gas

It is also possible to transport hydrogen in the natural gas network with relatively little modification, and this may be the best option if it can be brought about. Adding hydrogen to natural gas is an effective way of improving the combustion properties and cleanliness of the fuel, and the proportion of hydrogen can be gradually increased. This means of transporting hydrogen is limited to 15-20% hydrogen by volume, before modification of existing burners and other end-use technologies is required.

Storage issues are particularly challenging for vehicle uses, they generally revolve around volumetric density, gravimetric density, cost and, for vehicles, refill time. This is an active area of research in which the aim is to achieve the energy density of conventional fuels at a comparable cost.

Figure 8.1 summarises the present state of storage technologies. Data are compared relative to gasoline (100) on an equal range basis assuming that hydrogen is utilised in a fuel cell at an overall efficiency of 42%.

Figure 8.1: Hydrogen Storage for Vehicle: Current Technical Status



Notes: Cryogenic hydrogen comes closest but has high cost and high energy demands associated with manufacture, refuelling and boil-off make this an expensive option. The best option may be a combination of compression with adsorption. Conventional carbons are at the low end of the range shown. Increase in skeletal density and increase in specific adsorption of hydrogen could provide storage comparable with gasoline. H_2 storage using carbon nanostructures is under development through alternative approaches. It offers the potential for improving performance—some options are even able to store H_2 at relatively high energy densities near atmospheric pressure and ambient temperatures. Successful development of one or more of these technologies might make storing H_2 in fuel cell vehicles no more difficult than storing gasoline in gasoline internal combustion engine cars.

The estimated costs of storage, on-site facilities and re-fuelling times for the range of systems described above are summarised below:

Table 8.3: Costs and Refuelling Times for Hydrogen Compared with those for Gasoline

System	Container cost equivalent (50ltr gasoline tank)	Refuel time (mins)	Station costs $/GJ
Gasoline	30	2-3	0.6
Compressed	2000	3-5	4-6
Compressed and cooled	2000+	5+	5+
Liquid Hydrogen	500-1000	2-5	3.5-5
Hydride	1500-3000	20-30	3-4
Cryo adsorption	1000-2000	5	4-5

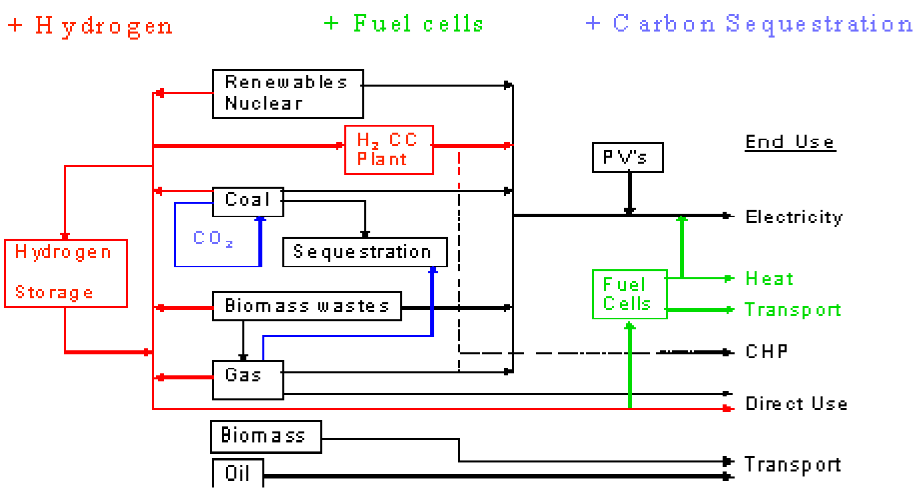
End use. Using hydrogen in conventional engines is perfectly feasible and produces almost no emissions, but there is some NO_X related to any high temperature combustion process and there are hydrocarbons associated with lubricating oils. The benefits of use in fuel cells are discussed above.

8.3 Systems innovation: the role of hydrogen and new 'energy vectors'

If deep cuts (around 50% or more) in carbon emissions are to be achieved in the long-term, then the development of the hydrogen option discussed above will become critical. There are two reasons for this. First, we will need a resolution of the intermittency problem of renewable energy. Second, we will need an alternative carbon-neutral fuel for the transport and gas markets, the most promising of which is hydrogen, which can be used for fuel cells or combustion.

It has been suggested, for example by the Royal Commission on Environmental Pollution (2000), that the UK might be able to reduce its carbon emissions by 60% by 2050, relative to carbon emissions in the1990s, by a large programme of investments in energy efficiency, nuclear power and carbon sequestration, plus some investments in 'intermittent renewables'. But this is to understate the possibilities ahead, since it is to neglect the role of hydrogen and the promise of fuel cells and other hydrogen using technologies. The energy system would then likely take on a very different form, as illustrated in Figure 8.3 Today's system is shown by the dark lines, the alternative system by the addition of the red and green lines.

Figure 8.3: Energy Systems With and Without Hydrogen as an Energy Carrier



Experiments with such systems are in fact beginning. For example several countries (including the UK) are introducing demonstration programmes of fuel cell vehicles, and supporting these with hydrogen fuelling stations. If such experiments succeed, they promise immense environmental and economic benefits: the prospect of a zero carbon and virtually pollution free energy system will have been demonstrated; and they will be a stimulus to the development of low cost electricity and heat based on fuel cells and/or micro-turbines (decentralised generation) on consumers' premises. There may also be benefits in terms of energy security, since it is thought possible to store hydrogen geologically on a very large scale, e.g. in salt caverns and depleted gas reservoirs.

For these reasons innovations at the *systems* level will need to take place along with innovations in the component technologies, discussed at length above. Historically, electricity and gas grids have evolved to serve five functions:

- to distribute energy, their primary function;
- to pool reserve capacity and enhance security of supply;
- to exploit economies of scale in generation;
- to improve capacity utilisation by taking advantage of regional diversities in the timing of peak demands; and
- to transmit energy in bulk from low-cost, fuel-rich areas.

There is the additional possibility of the grids ‘harvesting’ of off-peak and renewable energy from a diversity of small and large scale generators for the production and storage of hydrogen, for later use when demands are high.

8.4 Cross Cutting Technologies

Technological development in non-energy matters could have profound impacts upon energy production and use. Biotechnology in particular has potential to improve the efficiency and flexibility of biofuels. Nanotechnology, ICT and advanced materials science will all impact on the demand and supply for energy.

Biological science can enhance the yields of crops, increase the amount of usable energy recovered from biomass (such as wood and crop residues), ease the processing of energy crops and more speculatively be used to directly produce electricity and hydrogen from organic material.

Improvements in crop yields are not expected to radically enhance the contribution biofuels make to address climate change. Higher yields are often accompanied by the application of energy intense fertilisers (the production and use of which are associated with emissions of the potent greenhouse gas nitrous oxide).

Biotechnology might also directly exploit the underlying biochemical reactions outside of the original organisms. The theoretical potential is substantial. The photosynthesis reactions convert light into electricity with an efficiency of 80% compared to 15% for commercial PV and 40% for the best laboratory prototypes. However, there are still enormous challenges before this theoretical efficiency of the biochemical reaction can be exploited.

Research on artificial photosynthesis is being financed in Australia, US and Sweden. Photosynthetic pigments that capture the energy from sunlight are sandwiched between layers of material that donate and receive electrons to create an electric current. The Australian[30] team proposes assembling such units near to coal fired power stations utilising the excess heat and carbon dioxide emissions. Fundamental research still needs to be carried out and returns are not expected for 20 to 50 years.

Research on converting sugar (produced from waste organic material) to electricity and hydrogen is still at an early stage of development. Researchers[31] using a microbial fuel cell report an efficiency of 1.6% in terms of converting the energy in

[30] CSIRO
[31] *pers. Comm.* University of the West of England

sugar into motorised movement. Some researchers believe the scope for improvement is significant; in the short term by selecting strains of bacteria with higher electricity yields and in the long term through engineering bacteria to avoid their 'wasting' energy in growth and multiplication. In the US researchers are developing microbial fuel cells to power tiny internal drug delivery devices.

ICT is likely to play a key role in changing the nature of energy systems – improved control systems to improve process efficiency, remote load management and new ways of managing transmission and distribution of electricity are some options. The 'knowledge economy' is also likely to change the character of demand (high specific energy industrial to low specific energy knowledge production).

Research and developments in nanotechnology, superconductivity and advanced materials science will also have substantial impacts on the supply and demand of energy. For instance nano techniques could produce better and cheaper PV cells, new ceramics could produce lighter and more durable wind turbines and superconductivity could reduce electricity transmission losses, improve the efficiency of motors, and improve high temperature heat recovery and insulation. Much more work remains be done to exploit cross cutting technologies to reduce carbon use.

9 Assessment: Regional, Temporal and Technology Aspects

The technology discussions above demonstrate the range of options and alternatives that are emerging. But they differ widely in terms of technological maturity and costs – now and in prospect. Some technologies – energy storage for example – also offer the potential to 'open the door' to a greater variety of other low carbon options, we term such technologies 'enabling' options. It is equally evident that technologies differ greatly in terms of their suitability for the circumstances of different countries and availability in different parts of the world. Finally, technologies have diverse implications for non-carbon policy goals, particularly security of energy supply and non-carbon environmental impacts. In this section we therefore summarise:

- Regional variations in resource and appropriateness for different country circumstances.
- Temporal considerations, the maturity of each technology and expected cost reductions over time.
- 'Enabling technologies' – those that will play a facilitating role in the development of low carbon energy.
- Compatibility with other policy goals; particularly non-carbon environmental impacts and energy security.

9.1 Regional and socioeconomic considerations

Resources are far from evenly distributed on a global basis, and not all options are amenable to long distance shipment and transportation. Moreover, because the needs and circumstances of countries differ, some options offer greater usefulness and potential in some regions than in others. This is, of course, a complex array of subjects. We provide here a simple overview of two main aspects: regional resources; and suitability to economic and infrastructural circumstances. With the partial exception of renewable resource availability, the latter is by far the most significant driver of technology choice. In the long term, economic circumstances and infrastructural arrangements will change; we therefore consider the relevance of different technologies now and in the future.

Absolute variations in regional resources:

In aggregate terms, a wide variation in resource availability occurs in renewables. In the absence of large scale electricity transmission infrastructures or a new energy vector such as hydrogen, they are also highly location specific and difficult to 'move'. This can be a benefit – their distributed nature means some renewables are well suited to meeting local needs close to source. We therefore discuss renewable resource availability at most length in this section. Whilst 'conventional' fuels are also unevenly distributed, access to them depends largely on economic circumstance and infrastructural capabilities, and for this reason is discussed at more length in the subsequent section, however we would note the following:

Oil reserves are heavily concentrated in the Middle East, though significant resources are available in other regions; however oil is in many respects the most 'portable' of all fuels. Access is primarily a function of economics and therefore discussed below.

Gas reserves are also unevenly distributed, and access is dependent upon substantial investments in pipelines and facilities for liquefied natural gas; again we return to this below.

Coal resources are more evenly distributed. Coal is relatively costly to move large distances, but large and low cost coal reserves can provide a low cost energy source for several large energy users, not least India and China; we return to this below.

Nuclear materials are portable and relatively small physical quantities can, where appropriate generation technologies are available, deliver large amounts of energy. Access to nuclear power is therefore much more dependent upon the human and physical capital required for nuclear generation, and on the availability of infrastructure for energy delivery. For these reasons, we also return to this below.

Renewable energy

Solar resources are largest in tropical, subtropical and warm temperate latitudes. Annual insolation is typically three times greater in the tropics than in cool temperate regions. The most notable feature of solar energy is that it may be used with highly decentralised technologies that use the primary resource at source – BIPV, SWH and directly in buildings ('passive' solar design). Such technologies are able to provide energy at point of use, and are not dependent upon energy supply infrastructures. For this reason solar has three very important potential applications: provision of power in regions remote from existing electricity grids; provision of light and cooling in buildings; and meeting daytime electricity demands due to air conditioning. All these are of particular importance in developing regions.

Wind power varies within rather than between regions. As a result substantial wind resources are, in principle, available in most parts of the world. Wind is limited by three factors: availability of sites in locations with good wind speeds; accessibility of sites with good wind speed – some may be remote from existing electricity grids; and grid integration issues – generally speaking the smaller and less developed the grid infrastructure the lower the ability to assimilate large amounts of wind power. Nevertheless wind is likely to be able to make a useful contribution to energy supplies in many countries and a very substantial one in some.

Wave and tidal power are, of course, most easily accessed in coastal regions. The availability of these sources of energy will depend upon the development of appropriate transmission infrastructure, but it should not be assumed that this means that they are confined to island states or that this presents an insurmountable obstacle to development. It is notable that large urban areas are located on the seaboards of many continents; the US, Australia, China and India all provide examples.

Biomass is widely distributed. At present the potential for sustainable biomass exploitation appears to be much greater than current use in Europe, North and South America and parts of Africa. However, it appears that exploitation already exceeds sustainable supply in many parts of Asia and Africa – reflecting the importance of a shift away from traditional biomass to both modern biomass systems and other modern fuels in these regions. Geographical differences give rise to two distinct types of biomass opportunity given current technologies: In temperate regions the largest potential is in the form of woody crops and some grasses. These are currently most technically and economically viable for use in electricity generation and heat. Development of hydrolysis technologies would enable such crops to be used for biofuels. In some tropical countries, notably Brazil, where large land areas are available, it is possible to grow high yield sugar crops on a substantial scale. In these cases there is much larger potential to produce ethanol for use as a vehicle fuel using existing technologies.

Geothermal energy is widely distributed, but current technologies restrict development to regions where hydrothermal resources are easily accessible. Such resources are extensively available in the Pacific Rim countries, which suggests that geothermal could play an important role in many emerging economies – at least in so far as a substantial resource is available. In the longer term, developments in technologies for exploiting hot dry rocks could expand the scope of geothermal potential to a wider range of geological conditions.

Socioeconomic conditions and technology choice:

More important for technology suitability and applicability, at least in the near term, than absolute resource availability are the infrastructural and economic circumstances of different countries. The least developed regions face a major challenge in expanding supplies of modern forms of energy in order to facilitate economic development and to bring the benefits of energy services to poorer communities. At present, large areas of developing regions, particularly in Africa, have very limited energy supply infrastructures. Whilst many countries have made great progress in expanding access to modern forms of energy, around 1.6 billion people are still without access to reliable electricity supplies and other modern forms of energy (IEA 2002). It is likely to take several decades for electricity grid extension to reach the poorest and most remote regions of many countries. Grid expansion is capital intensive and expensive, and can place substantial strains on the financial resources of electricity utilities, whether private or publicly owned. Moreover many countries operate old fashioned and inefficient generating plant and systems exhibit high levels of transmission and distribution losses. Even in large cities power shortages and power cuts are still commonplace in parts of the developing world.

It is important therefore that any discussion of the development of low carbon energy is placed within a context that acknowledges that developing efficient, reliable supplies at minimal cost is an over-riding priority in many parts of the world. Technology choice under the diversity of economic circumstances that prevail in the world today is a complex subject, way beyond the scope of a short report such as this. However, we would note the following:

Efficient exploitation of domestic resources is a major priority: India and China have substantial coal reserves, that offer the lowest cost fuel source in many applications, and coal is likely to continue to provide for much of the growth in energy supply in these countries. Coal is a high carbon fuel, but utilising it in old fashioned and inefficient plant also gives rise to substantial local pollution problems. Inefficient and unreliable plant and transmission equipment also militates against cost effective and economically optimal use of the resource. Moving to improved coal technologies would improve local air quality, reduce carbon intensity by 50% or more and deliver energy at improved economic efficiency.

Switching to more efficient and cleaner ‘conventional’ fuels remains a key priority for development, to reduce local pollution and other environmental problems *and* in climate change terms. Large-scale delivery and exploitation of natural gas for domestic and commercial direct use, and for power generation, is one example. At the other end of the scale, access and affordability of kerosene and liquefied petroleum gas (propane) for cooking in rural and peri-urban areas can bring great benefits in terms of local air quality, labour saving and quality of energy service provision.

Some low carbon options are better able to meet local needs than conventional alternatives: this appears to be particularly true in the case of rural electrification. The potential for off-grid PV systems to provide modest amounts of electricity at lowest cost in remote regions has already been noted. However, where liquid fossil fuel supply infrastructures are available, ‘conventional’ decentralised options for small scale electricity generation also offer considerable potential, and should not be overlooked. As the costs of micro-turbines and micro-CHP technologies are reduced they may be able to provide considerable benefits to remote and rural communities.

As economic development progresses, and requirements for (and ability to afford) more substantial amounts of energy increase, other emerging options may offer considerable benefits: facilitating efficient small scale generation for ‘micro-grids’ that supply towns and villages provides one example. This may prove to be a more cost effective means to provide high quality power supplies than through grid extension in some cases, particularly in larger and more sparsely populated regions. Advanced control technologies, micro-turbines and even fuel cells could play an important role in developing supplies of this nature.

Developing regions can move straight to some more efficient and cleaner end use technologies and thus take a less polluting and carbon intensive development path than was taken by developed countries. In many cases such technologies are both economically attractive and environmentally less damaging. Examples include vehicles, industrial processes and low energy urban buildings.

Overall it is not possible to provide a simple hierarchy of the relevance of different technologies for different regions. Large-scale power generation facilities best suited to mature and large-scale transmission grids are often of limited use in provision of energy services to those currently without access. However, this does not mean that developing countries do not require such technology – as the examples of efficient coal and access to gas supplies indicate. As a result, an increasing diversity of energy technology choices appears likely to be a major characteristic of future developments in both developing and OECD countries. The medium term future is likely to include:

- Expansion of highly efficient fossil fuel generation technologies and supplies of natural gas in large urban areas in developing regions as well as the OECD.

- A general trend towards smaller scale and more distributed generating sets.

- Early exploitation/demonstration of carbon sequestration where policies encourage this.

- Development of PV for small-scale off-grid demands.

- A shift from traditional biomass to conventional liquid fossil fuels such as kerosene and propane for cooking and water heating.

- An expanding role for solar water heating in sunny latitudes.

- Development of micro-grids, with a mixture of renewables (including PV, biomass, microhydro and wind) and fossil fuelled generation for rural towns and villages.

- Exploitation of biofuels for transportation in some developing regions, notably Brazil.

- Wider exploitation of modern biomass.

- Development of wind energy and other grid connected emerging renewables is likely to continue to be dominated by OECD countries for some years, but important niches will also be exploited in developing regions .

- Continued improvements in efficiency in end use devices, particularly where policies encourage development by manufacturers and adoption by consumers.

- 'Leapfrogging' direct to high efficiency end use and conversion technologies in developing countries.

The latter point highlights the fact that in the long term, but certainly within the 50 year time horizon of this study, innovation and economic progress will change the entire picture. As a result, attempts to predict technology mixes in the far future are speculative. Nevertheless, in the following section we consider some key aspects along the road to 'the world in 2050'.

9.2 Temporal aspects:

1 Technological maturity

As discussed in more detail above, low carbon technologies differ widely as to their technological maturity. We summarise here (table 9.1) the main options in terms of where they broadly fit on a spectrum of technological maturity from 'conceptual' options, still at the basic research stage, through 'emerging' options that are proven in terms of technological viability and have some market exposure, but which still require development and market growth to realise cost reductions and more widespread utilisation, to ‘mature’ options that are at an advanced level of technological development and commercially viable (though may not yet have achieved widespread utilisation). On the basis of this we provide an overview of the timeframe in which each technology *could*, if development is successful, come into widespread utilisation (Table 9.1).

Table 9.1 Technology maturity

<table>
<tr><th>Conceptual</th><th>Emerging</th><th>Mature</th></tr>
<tr><td>Fusion
Advanced fission
Photosynthetic hydrogen</td><td></td><td></td></tr>
<tr><td colspan="2">Advanced PV
Wave and tidal stream
Hydrogen storage for vehicles
Biomass (hydrolysis)
Geothermal (hot dry rocks)</td><td></td></tr>
<tr><td></td><td>Fuel cells for vehicles
Offshore wind
Various energy storage technologies
Biomass (gasification)
Carbon separation and storage
Nuclear power (next generation reactors)</td><td></td></tr>
<tr><td></td><td colspan="2">Onshore wind
Fuel cells for stationary use and CHP
PV for buildings
Biomass (combustion)
Hybrid vehicles
LED lighting
Biofuels (ethanol and biodiesel from oil seeds and starchy crops)
Micro-CHP
Advanced metering and control technologies</td></tr>
<tr><td></td><td></td><td>Numerous end use efficiency options in appliances and buildings
Nuclear power (current reactors)
Geothermal (hydrothermal)
Large and small hydro-electricity
Biomass (co-firing)
Tidal barrages
Offgrid PV
Large and medium scale CHP</td></tr>
</table>

2 Costs of low carbon energy today and in prospect

Numerous studies have estimated future costs of low carbon technologies. One example is provided in part 1 above. The expectation is that the costs of the renewable energy technologies and other emerging options will decline relative to those of current fossil fuelled options and nuclear power. This is because most technologies are in their infancy and the scope for further cost reductions through R&D, scale economies and 'learning-by-doing' is appreciable.

Although innovation in fossil fuel and perhaps nuclear technologies will also proceed, as discussed earlier, technologies that are in their earlier phases of development, and which have been relatively unexplored typically show the highest rates of technical progress. It should also be borne in mind that historical expenditures on the development of both nuclear energy and fossil fuels outweigh those on renewable energy by at least three and perhaps four orders of magnitude; the scope for 'catch up' is appreciable.

Nevertheless, in the near term costs are generally higher than those of fossil fuels. Even quite small differences in costs between alternative technologies can and does lead to major switches from one technology to another. For example, a 1p/kWh (0.57 US cents) differential in the costs between one 1000MW power plant and a lower cost alternative competitor leads to a financial loss of £80million ($120million) per year in competitive electricity markets.

How *long* it might take for technologies to reach 'maturity' such that they are able to achieve substantial cost reductions, overcome technical obstacles, and/or secure a substantial fraction of their potential market is difficult to predict. Technologies differ in terms of their market growth and the rate at which they are progressing in technical terms. We provide an indication of the rate at which technologies might be expected to develop in part 1.

9.3 The development of key enablers

'Enabling technologies' are those that will permit more widespread utilisation of other low carbon technologies. The most important options are electricity storage, to help overcome the intermittency of some renewables, advanced metering and control technologies that ease the integration of small scale electricity generation technologies into the power grid, and hydrogen storage and transmission – which would provide both energy storage for intermittent renewables and a zero carbon fuel for vehicles.

We consider here the prospective costs of the most ambitious and far reaching of these, hydrogen. Initial calculations suggest that the costs would not be prohibitive (Table 9.2). Hydrogen as a fuel is bound to be more expensive than natural gas or oil, but it does hold out the prospect of cheaper electricity—and, as discussed, the benefits of virtually pollution free energy.

Table 9.2 Unit costs of hydrogen system: current and prospective (p/kWh), compared with current retail prices of electricity and gas in the UK

Component of Cost	Costs p/kWh: Current	Costs p/kWh: Prospective	Costs (p/kWh) of Comparator	Comments
Costs of Intermittent Renewable Energy	3.0	2.0		
Electrolysis (a)	1.0	0.5		
Compression and Storage in Reservoirs (b)	1.5	0.5		
Average Costs of Distributing Hydrogen (c):				
Industrial Consumers	0.3	0.3		
Residential Consumers	1.8	1.8		
1. Total Average Costs of Hydrogen:			**Natural Gas:**	
Industrial Consumers	5.8	3.3	0.7	
Residential Consumers	7.3	4.8	1.7	
2. Marginal Costs of Electricity:	**Hydrogen as Fuel:**		**NG as Fuel:**	Combined Cycle for Off-peak, Gas Turbines at Peak for NG and H fuels
HV supplies at peak	31.5	24.2	16.9	
HV supplies at off-peak	8.3	5.0	1.3	
LV supplies at peak	41.8	34.1	26.4	
LV supplies at off-peak	9.8	6.3	3.4	
3. Average Costs of Electricity:				
HV Supplies	10.5	6.8	2.8	
LV Supplies	15.4	8.9	5.6	
4. Average Costs of Electricity in UK:			**Current UK Fuel Mix:**	
HV Supplies			3.6	
LV Supplies			8.5	
5. Average Costs of Electricity if Fuel Cells Were Used for Distributed Generation (f):	**Hydrogen as Fuel:**		**NG as Fuel:**	
In Industry (current FC price of £2000/kW)	14.7		6.7	Future fuel cells incl. use for CHP
In Homes (Current FC price)	17.5		8.5	
In Industry (Future FC price of £500/kW)		5.8	2.4	
In Homes (Future FC price)		7.9	3.8	

a/ Electrolyser costs of £400/kW (today's prices) and £200/kW (prospective prices), 80% efficiency, and 70% utilisation. From Joan Ogden (1999).
b/ Ibid. Ogden quotes costs of \$2-6/GJ (0.5-2.0p/kWh), though adds that for seasonal storage the costs are higher.
c/ The costs of hydrogen transmission and distribution are taken to be 1.5 times the costs of distributing natural gas, based on discussions with industry. The costs of distributing natural gas are taken to be approximately equal to the average prices paid for natural gas in the UK (respectively 1.7 and 0.7 p/kWh for domestic and industrial consumers, shown in the second column of the following set of rows) less the costs of exploration, production and transmission to the gas grid entry points, which from IEA data on border prices appear to average around 0.5 p /kWh. The UK price data are taken from the *DTI Digest of UK Energy Statistics, 2000*.

9.4 Environmental impacts

No technology is entirely without environmental impact. For all technologies CO2 emissions are associated with the manufacture and installation of equipment, as the energy required for these activities will (at least at present) be derived from conventional energy sources. This also results in emission of other pollutant gases associated with conventional energy supply – notably oxides of nitrogen and sulphur. However for all of the renewable technologies considered here the 'energy balance' is strongly positive – that is the technologies supply much more energy (or save more CO_2) during the course of their useful lives than is required in installation. The same is true of nuclear power and CO_2 storage and energy efficiency. As a result 'lifecycle' emissions of CO_2 and other pollutants are very low compared to fossil fuels – less than 1% in the case of wind power for example – see Table 9.3.

Table 9.3: Specific emissions by generation type

Pollutant g/kWh	Gas (CCGT)	Coal (steam FGD)	onshore wind
NOx	0.46	2.2	0.03
SOx	Negligible	1.1	0.02
CO2	484	848	10

The non-carbon environmental impacts of renewables are wider and more diverse than air pollutants and greenhouse gases. The impacts include:
:

- Visual intrusion, normally associated with onshore wind and extremely difficult to quantify.
- Noise, again primarily associated with onshore wind. Older turbines are noisy; however improved design has drastically reduced noise and well sited turbines can almost entirely avoid any significant impacts on populations living nearby.
- Impacts on the marine environment – wave, tidal stream and offshore wind will entail some environmental disruption during construction. However such impacts do not appear substantial in most areas, the devices are benign once in place and may provide 'artificial reefs', to the benefit of marine life.
- Utilisation of potentially toxic materials such as heavy metals. This issue primarily affects photovoltaic panels, some designs of which involve the use of materials such as cadmium and gallium arsenide. Widespread use would require careful controls on disposal of old panels.
- There is some evidence that PV for off-grid electricity in developing countries is increasing the amount of waste lead (from batteries) in rural environments with very limited waste infrastructures. The scale of this problem is not yet clear.

The other low carbon options that have significant environmental impacts are nuclear power and separation and storage of CO_2, these are discussed in section 6, above. In both cases long-term environmental risks are more significant than routine emissions.

Any attempt to quantify such diverse impacts in a way that allows meaningful comparison is fraught with difficulty. It is notable however that energy efficiency improvements are largely free of additional environmental impacts and that the impacts of renewables are largely localised, involve little or no long term or dangerous components (with the exception of heavy metals and batteries) and are largely reversible – technologies can be decommissioned and removed and impacts reversed or erased. For these reasons energy efficiency and renewables are the lowest impact technologies.

9.4 Security of supply

Security of supply has two interrelated aspects: geopolitical aspects that surround the relations between countries and regions that supply and use energy and 'keeping the lights on', maintaining energy provision in a technical sense. This is a complex subject and only general observations are possible here:

- Efficiency is the only clear and uncomplicated 'winner' amongst the low carbon options discussed above, in terms of its contribution to improving both aspects of security of supply. Energy efficiency can reduce dependence on unstable or hostile regions, improve the capacity of existing grids and networks to meet demand (and delay the need for upgrading), and prolong the potential contribution of existing energy supplies. For the other options the picture is rather more mixed.
- Nuclear power and renewables can reduce dependency on fossil fuels, which generally improves geopolitical aspects. However both have technical implications: large penetrations of intermittent renewables require changes to the nature of electricity grids, demand management and/or storage; whilst nuclear power, at least with current technologies, is inflexible in operation and unable (alone) to respond rapidly to changing demands. Neither of these problems is unassailable, particularly in the long term, as discussed above.
- Carbon sequestration has the potential to diversify supplies, if applied to coal, which can ease both geopolitical and, in future, absolute supply constraints (global coal reserves are both larger and more widely distributed than those of other fossil fuels). But as natural gas is in many cases the lowest cost route, and could be used with sequestration to provide hydrogen for transport fuel, it has the potential to transfer the current dependence of transport from oil to a dependence upon gas.
- The use of hydrogen as a vehicle fuel provides the opportunity to use a wider diversity of primary sources in this sector as hydrogen may be made in a variety of ways and from several feedstocks. Development of hydrogen is also one of the means by which to ease the problems associated with intermittency (see above).

This report can only provide a brief overview of the cross-cutting issues discussed above; nevertheless, we summarise the main aspects in Table 9.4 below. The issues are not straightforward and it would be a mistake to attempt crudely to 'rank' technologies on the basis of this matrix; this is not its purpose. However, it does provide a useful overview of the 'fit' of each technology in terms of its regional suitability, maturity and potential for cost reduction and contribution to other policy goals.

Table 9.4: Summary of technology assessment

Option	Maturity	Scale & modularity	Current costs	Cost reduction potential	Regional aspects	Impacts on other policy goals (security, environment)
PV	Emerging	Very small, modular	High (on-grid), Low (off-grid)	Very large	Off-grid prospects, good resource in DCs	Positive, but intermittency an issue
Wind	Emerging to mature (onshore)	Small, modular units (may be deployed in large farms)	Moderate	Moderate	OECD in medium term (grid supplies), large offshore resource	Positive, but intermittency an issue, siting constraints in some regions
Geothermal	Mature (hydrothermal) conceptual (others)	Medium	Moderate	Moderate	Excellent resource in Pacific Rim	Generally positive
Wave & tidal (not barrages)	Emerging	Small to medium, modular	High	Large	Coastal regions worldwide	Generally positive
Tidal Barrage	Mature	Large	High	Very low	Limited sites	Negative local environmental impacts
Nuclear	Mature	Large	Moderate	Moderate to low	Grid and well developed infrastructures required	Negative environmental impacts (risks), proliferation problems
CO2 C&S	Emerging, based on mature components	Large	Moderate	Moderate to low	Global resource, large infrastructure required	Generally positive, concerns surround environmental risks
End use efficiency	Mature, but many emerging and conceptual possibilities	Small	Very low	Low for existing options, high for emerging	Global potential, including 'leapfrogging' by DCs	Positive implications for security and environment
Supply and transmission efficiency	Mature, but many emerging and conceptual possibilities	Large and small scale options	Low	Low for existing options, high for emerging	Global potential, including 'leapfrogging' by DCs	Positive implications for security and environment
Hydrogen and energy storage	Emerging	Large and small scale options	High	Very high	Facilitates profound changes to nature of global energy system	Positive implications for security and environment

Contributors and Consultees

This report was written and assembled by Robert Gross and Dennis Anderson for Imperial College Centre for Energy Policy and Technology, with section drafting, technical details and comments from a team of experts at ICCEPT and other organisations:

Main Contributors (ICCEPT)

Prof Dennis Anderson

Dr Ausilio Bauen

Dr Chris Clark

Prof David Fisk

Dr Tim Foxon

Robert Gross

Prof Michael Grubb

Dr David Hart

Dr Matthew Leach

Dr Peter Pearson

External contributors

Gordon MacKerron (NERA)

Dr Catherine Mitchell (Warwick Business School)

Dr Paul Rutter (BP)

Dr Peter Taylor, Dr George Marsh (Future Energy Solutions, AEA Technology plc)

Prashant Vaze, Strategy Unit

Consultees

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Prof Michael Laughton	Queen Mary College, Royal Academy of Engineers
Chris Mottershead	BP
Harry Bradbury	Intelligent Energy
Anthony Derrick	IT Power
Mark Pyman	Shell
Charles Liebenberg	Investec
Fred Dinning	Scottish Power
Demitrios Papathansiou	World Bank
Dr Chris Anastasi	British Energy
Prof Jim Skea	Policy Studies Institute
Dr Bernie Bulkin	BP
Ged Davis and others	Shell
Prof David Elliott	Open University
Prof Jake Chapman	
Prof Tim Jackson	University of Surrey
Dr Jack Frost	Johnson Matthey
Graham Smith	Toyota UK
Tom Delay	Carbon Trust
David Vincent	Carbon Trust
Catherine Bremner	Carbon Trust
Gayner Hartnell	Renewable Power Association
Prof Alan Williams	Leeds University
Catriona Laing	Strategy Unit
John Furlong	Office Science and Technology (OST)
David Hayes	DTI
Dr Jeremy Eppel	Defra
Nick Mabey	FCO
Caroline Reeves	OST, Research Councils
Dr Amal-Lee Amin	FCO
Dr Jeremy Leggett	Solar Century
Joanne Wade	Association for the Conservation of Energy
Leslie Packer	DoT
Dr Michael Jacobs	Fabian Society
Dr Doug Parr &	
Matthew Spencer	Greenpeace
Dr Nick Eyre	Energy Saving Trust

Glossary

AGR stations	Advanced Gas Cooled Reactor nuclear power stations
BAU	Business As Usual
Biofuels	A fuel produced from dry organic matter or combustible oils produced by plants.
Biomass	The total dry organic matter or stored energy content of living organisms.
Carbon abatement	Reducing/diminishing carbon produced, measures to prevent CO_2 emissions
Carbon capture	Removal of CO_2 from fossil fuels either before or after combustion. In the latter the CO_2 is extracted from the flue gas.
Carbon storage	The long-term storage of carbon/CO2 or carbon underground in depleted oil and gas reservoirs, coal seams, and saline aquifers
CHP	Combined Heat and Power
CCGT	Combined Cycle Gas Turbine
CO_2	Carbon Dioxide (a greenhouse gas)
DCs	Developing countries
Decentralised generation	Electricity generation that supplies direct to local electricity distribution networks, close to demand
Greenhouse gas	Atmospheric gases that partly absorb and re-emit downwards infrared radiation emanating from the earth's surface.
DTI	Department of Trade and Industry
EC	Commission of the European Union
EU	European Union
EST	Energy Saving Trust
Externalities	An action by any producer/consumer that directly impacts on another producer/consumer, which the latter has not chosen to accept and so is not reflected in the market price of the action.
Fuel cells	An energy conversion device which produces electricity from the electrochemical reaction between hydrogen and oxygen.
GW	giga Watt – a measure of power, one billion Watts.
IEA	International Energy Agency
ICE	Internal Combustion Engine
Intermittents	Intermittent power plants harness energy from unpredictable natural sources (for example, wind or waves). Output is therefore not reliable, in the sense that it cannot be turned on and off as required.

IPCC	Intergovernmental Panel on Climate Change
kWh	kiloWatt hour. Unit of electrical energy - one thousand Watts of power provided for one hour. The basic unit of electricity sales.
Low carbon options	All technologies that serve to reduce carbon emissions; by improving the efficiency with which carbon based energy is used, by using carbon free or non-net carbon sources, through carbon storage
LNG	Liquified Natural Gas
Micro-generation	Generation of electricity on a very small (e.g. domestic scale), for example by photovoltaics or fuel cells.
Micro-turbines	Gas turbines operating on a small scale, one of the technologies associated with micro generation
MW	mega Watt – one million Watts
MWh	mega Watt hours – one thousand kWh
Non-net-carbon	Energy sources that emit carbon to the atmosphere but also absorb it – essentially applied to biomass
NO_x	Nitrogen Oxides (local air pollutants)
OECD	Organisation for Economic Co-operation and Development
OPEC	Organisation of the Petroleum Exporting Countries
Photovoltaics	Apparatus which transforms sunlight into electricity
PIU	Performance and Innovation Unit, now the Prime Minister's Strategy Unit, UK govt Cabinet Office
PV	Photovoltaics
p/kWh	Pence per kWh – the common form of pricing energy sold to consumers.
RD&D	Research, Development and Demonstration
R&D	Research and Development
RCEP	The Royal Commission on Environmental Pollution
PWR	Pressurised Water Reactor, a type of nuclear power station
SO_x	Sulphur Oxides (local air pollutants)
SWH	Solar Water Heaters
TOE	Tonnes of Oil Equivalent, a measure of energy
TWh	One billion (1,000,000,000) kWh
TWh/yr	Units of electrical energy produced/consumed in a year
UNFCCC	United Nations Framework Convention on Climate Change
Watt (W)	The standard (SI) unit to measure a flow of energy.

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